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Analysis of Rotorcraft Crash Dynamics for Development of Improved Crashworthiness Design Criteria

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16. Abstract
A review was conducted of U.S. civil helicopter accidents occurring between 1974 and 1978 to determine impact conditions and injuries to the occupants. This report describes the distribution of impact conditions. Also, six typical impact scenarios were developed to represent classes of accidents. A rank-ordered analysis of crash hazards is presented. The report also contains an evaluation of computer techniques available for structural crash dynamics simulation and a comparison of the civil and military helicopter crash environments. Recommended crashworthiness design criteria for civil rotorcraft are presented.

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FOREWORD

This report was prepared by Simula Inc. under Contract No. DTFA03-81-C-00035 with the Federal Aviation Administration Technical Center, where L. M. Neri acted as Technical Monitor. Bell Helicopter Textron assisted Simula Inc. as a subcontractor in the accident evaluation effort.

The Simula Inc. Program Manager was D. H. Laananen. J. W. Coltman was the Project Engineer for the accident evaluation, injury assessment, and design criteria tasks. A. O. Bolukbasi conducted the evaluation of analytical techniques for structural crash dynamics simulation. The following persons provided valuable assistance in the accident evaluation phase: R. G. Fox and C. W. Raines of Bell Helicopter Textron, R. L. Jenny and W. E. Taylor of The Enstrom Helicopter Corporation, C. L. Fuller and B. L. Carnell of Sikorsky Aircraft, and J. E. Hicks and B. H. Adams of the U.S. Army Safety Center.

The evaluation of analytical techniques was supported by J. D. Cronkhite of Bell Helicopter Textron and C. E. Nuckolls* of the FAA Technical Center.

*Currently at the University of Central Florida.

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EXECUTIVE SUMMARY

This study was commissioned by the Federal Aviation Administration (FAA) Technical Center to evaluate impact conditions and injury-producing mechanisms in civil rotorcraft accidents. The goals of this study were to evaluate the state of the art of crashworthiness in the current rotorcraft fleet and to provide a data base to support future FAA rule-making efforts. The research effort was divided into four major tasks, as described below.

- Task I - Review all civilian helicopter accidents for 1974-78 (the most recent five-year period available), and where possible, determine the aircraft velocity and attitude at impact. The outcome of this work was a statistical distribution of impact conditions and a set of six scenarios that represent a significant percentage of the accidents examined.

- Task II - Tabulate injuries, and where possible, the injury-causing mechanisms. Fourteen specific hazards were identified. These mechanisms were ranked by frequency and severity in order to recommend priorities for improvements in hazardous components.

- Task III - A review of available analytical computer models with potential application to rotorcraft crashworthiness design and evaluation was conducted. The analytical techniques included finite element, lumped mass, hybrid, and modal analysis systems. Programs developed for individual elements, components, airframe sections, and complete rotorcraft were examined.

- Task IV - A review of crashworthiness principles outlined in the U.S. Army's Aircraft Crash Survival Design Guide was conducted to determine their applicability to civilian rotorcraft.

All records for rotorcraft accidents occurring during the five-year evaluation period (a total of 1,351) were examined at the NTSB office in Washington, D.C. Copies of all reports containing accident site photographs or information describing the accident or events leading up to it were obtained. Accident cases containing insufficient data to establish the impact conditions or those pending litigation were deleted from the sample. The resulting sample contained 311 accidents for the five-year period.

An evaluation team was established to analyze the available data for each accident. Simula Inc. personnel conducting the study were present for all accident evaluations, providing expertise in determining human tolerance, establishing the crash environment within the cockpit or cabin, and in using the techniques of accident reconstruction. Whenever possible, representatives of the manufacturer of the aircraft model involved participated in the evaluation effort. Three manufacturers, Bell Helicopter Textron, Inc., the Enstrom Helicopter Corporation, and Sikorsky Aircraft, participated in the evaluation team meetings for accidents involving their aircraft. Approximately 77 percent of the 311 accidents were evaluated with the aid of the manufacturers.

When the manufacturers were not able to support the program, personnel from the U.S. Army Safety Center, Fort Rucker, Alabama, participated in the evaluation effort for accidents involving aircraft models having military counterparts. These accidents accounted for approximately 10 percent of the sample. The remaining accidents were evaluated by Simula personnel.

During the reconstruction of each accident, an assessment was made of the potential for survivability. Accidents were judged to be survivable or partially survivable. The data presented in this report are based on survivable accidents meeting a minimum injury or damage criteria. These accidents were judged to be survivable, and met one or more of the following criteria: occurrence of postcrash fire, at least one minor or serious injury, and/or substantial structural damage.

The accidents were evaluated with consideration given to the size of the aircraft. This was accomplished by evaluating the accidents according to four weight classes based on maximum gross takeoff weight. The four aircraft weight classes were: less than 2,500 lb, 2,501 to 6,000 lb, 6,001 to 12,500 lb, and aircraft greater than 12,500 lb. It was found in the study that there was not a significant difference between the typical impact conditions and injury-causing mechanisms for the four weight classes.

Six crash scenarios were developed to represent the various types of accidents which were identified in the study. These six scenarios included approximately 79 percent of the accidents surveyed. The specific scenario types were: vertical impact, longitudinal impact, rollover, wire strike, water impact, and high yaw rate impact. In terms of the number of injuries occurring in accidents of each type, the vertical impact scenario was the most hazardous. Both the water impact and wire strike scenarios were found to produce significant numbers of injuries. Longitudinal impact, rollover, and high yaw rate impact scenarios were found to be much less hazardous.

The civil crash environment characteristics were compared to those determined for military helicopters. It was found that military design velocities (which were derived from a similar study sponsored by the U.S. Army) in the vertical and lateral directions were more severe than those identified for the civil accident data. Based on this comparison, it was determined that current military design criteria would be too stringent for civil rotorcraft.

The crash force magnitudes imposed on an occupant in the crash environment were compared to levels of human tolerance. It was found that for a well-restrained occupant, only the vertical impact forces exceeded the levels expected to produce serious injuries (mainly spinal injuries). This indicates a need to require vertical energy absorption in the landing gear, airframe, or seats to maintain a tolerable environment for the occupants. In the longitudinal and lateral directions, the crash environment is not expected to produce decelerative loadings that exceed tolerable levels for a properly restrained occupant.

Fourteen hazards, or injury-causing mechanisms, were identified for the civil crash environment. These 14 hazards were ranked according to their frequency of occurrence and the severity of injuries that were produced. It was found that there were four predominate hazards that should be addressed to improve civil rotorcraft crashworthiness. These hazards include (in order of severity): thermal injuries from postcrash fire, failure of the restraint system to protect

against secondary impact, excessive vertical impact loads transmitted to the occupant, and inflight wire strikes which result in uncontrolled flight.

The number and severity of injuries occurring in "survivable" civil rotorcraft accidents justify the need for upgraded design requirements. For example, based on an average yearly rate of the five years examined, approximately 40 percent of the survivable accidents had injuries and/or fatalities. There were an average of 545 occupants involved in survivable rotorcraft accidents per year. Out of these 545 occupants 23 were fatally injured, 57 received serious injuries, and 95 sustained minor injuries.

Based on the crash conditions identified for civil rotorcraft in this report, recommended design criteria for certification of new rotorcraft models are presented. The recommended approach is based on providing protection up to and including the 95th-percentile survivable environment for the current fleet of rotorcraft. The 95th-percentile survivable level of protection appears to be both reasonable and attainable within the development period of the next generation of commercial helicopters.

This report also identifies tasks recommended for future funding by the FAA. These tasks include the following:

- Detailed Design Criteria/Design Guide
- Prototype Crashworthy Rotorcraft Demonstration Project
- Cost/Benefit Analysis For Crashworthiness Improvements
- Enhancement of Analytical Methods
- Improved Crash Investigation Procedures.

1.0 INTRODUCTION

The design of future crashworthy civilian helicopters requires a comprehensive knowledge of the crash environment for such aircraft The primary objective of this contract effort, entitled "Rotorcraft Crash Scenarios," was to provide such knowledge. Similar work was undertaken by the United States Army in the 1960's and again in the 1970's for military rotorcraft, the results of which are published in the Aircraft Crash Survival Design Guide, USARTL-TR-79-22 (references 1 through 5), MIL-S-58095(AV) (reference 6), and MIL-STD-1290(AV) (reference 7). However, preliminary studies indicate that significant differences exist in the impact conditions between military and civilian helicopter accidents. These differences could greatly influence crashworthiness design requirements for future civilian helicopters by shifting the relative importance of various crash survival factors. Compared to civilian aircraft, the process for achieving crashworthiness in military aircraft is more direct, because the procuring agency is also the ultimate user. In the civilian sector, crashworthy improvements to helicopters can only be uniformly achieved through regulations implemented by the Federal Aviation Administration (FAA). Formulation of these regulations and their acceptance by the users must be based upon a clear indication of the need and economics for such changes.

The major goal of this research effort was to define typical crash conditions for civilian helicopters. The survivable conditions established in this study define the level of crashworthiness in existing aircraft, and suggest areas where potential improvements could be made. The four main objectives of this research effort were to provide a definition of the typical types of crashes or "scenarios," to examine the impact conditions associated with those scenarios, to analyze the factors causing injuries or fatalities in helicopter accidents, and to identify existing analytical techniques that could be used for component design. The tasks that comprised this program are described in further detail below:

- Task I

  Review all civilian helicopter accidents for 1974-78, the most recent five-year period available, and, where possible, determine the aircraft velocity and attitude at impact. Data were categorized with respect to weight, configuration, type of crash environment, operational mode, attitude, injuries, structural damage, and postcrash hazards such as fire. Evaluation of the accidents was conducted with the aid of engineers from the aircraft manufacturer whenever possible. Three manufacturers agreed to participate in the task: Bell Helicopter Textron, Enstrom Helicopter Corporation, and Sikorsky Aircraft. The outcome of this work is a set of six scenarios that represent a significant percentage of the accidents examined and the impact conditions associated with those scenarios.

- Task II

  Tabulate injuries, and where possible, the injury-causing mechanisms. Determining the pathological cause of injury implies an understanding of human tolerance in this type of crash environment. For an

occupant restrained by lap belt and shoulder harness, human tolerance to crash impact conditions is well documented (reference 2). However, for lap-belt-only restraint, there is a reduced tolerance to decelerative-type injuries, and test data are generally less complete. An effort was undertaken to collect all existing human volunteer test data for lap-belt-only restraint tests (reference 8). Injury-causing mechanisms were ranked by frequency and severity in order to recommend priorities for improvements in hazardous components.

- Task III

  A review of available analytical computer models with potential application to rotorcraft crashworthiness design and evaluation was conducted. Consideration was given to input data requirements, computational methods, output data provided, operating time and cost, level of operational experience required, documentation availability and completeness, degree of experimental verification achieved, and the most desirable use associated with each technique. Limitations such as cost and degree of modeling fidelity, as well as technical deficiencies, were evaluated. The analytical techniques included finite element, lumped mass, hybrid, and modal analysis systems. Programs developed for individual elements, components, airframe sections, and complete rotorcraft were included. The need for testing to verify analytical techniques, evaluate current crash criteria, develop and evaluate crash dynamic design procedures, and verify design improvements was assessed.

- Task IV

  A review of crashworthiness principles outlined in the U.S. Army's Aircraft Crash Survival Design Guide (references 1 through 5) was conducted, to determine their applicability to civilian rotorcraft. In addition, consideration was given to concepts and features of new and near-term military designs, and an investigation was conducted to determine whether any of the military design features might also be adaptable to the civilian fleet.

The scenarios defined in Task I and the injury patterns developed in Task II, combined with a review of current military design practices, identify areas requiring additional research in order to provide improved rotorcraft crashworthiness. Recommendations were developed for improved crashworthiness design criteria and for areas that need further research and development. This final report details all aspects of the rotorcraft crashworthiness study. An Interim Report (reference 9) was submitted earlier in the program describing in detail the Task I effort.

This program was intended to evaluate typical crash conditions for all sizes of civil helicopters. However, there was a general lack of accident data for rotorcraft larger than 12,500-lb maximum gross weight. Although many of the recommendations based on crash conditions for smaller rotorcraft may apply, there is presently not sufficient data to verify this assumption.

This report is organized into sections which represent the steps that were followed in completing this program. Section 2.0 discusses the procedures used

in selecting accident data, contains a description of typical impact conditions, and presents a set of six typical crash scenarios. Results of the injury/hazard analyses are presented in a statistical format in Section 3.0. Section 4.0 compares the civil rotorcraft crash environment to the military crash environment and the human tolerance data. In Section 5.0, conclusions are presented based on the data collected during the research effort. Section 6.0 contains recommendations for crashworthiness design criteria and future work. The work conducted during Task III, Evaluation of Analytical Methods, is detailed in Appendix A.

2.0 EVALUATION OF IMPACT CONDITIONS AND TYPICAL CRASH SCENARIOS

Improving the crash safety potential of future civilian helicopters requires first establishing the baseline crashworthiness performance of existing aircraft. Task I was conceived to evaluate actual impact conditions for as many recent accidents as possible and to determine under what conditions an occupant could be expected to survive. This, of course, assumes that human tolerance to impact and acceleration, and the techniques for assessing impact orientation and velocity have been conclusively defined, when in fact this is not always the case. Maximum levels of tolerable impact conditions vary widely with human skeletal strength. Also, engineering judgements are necessary for determining impact conditions from descriptions and photographs of accident damage. However, in the majority of accidents evaluated in this study, it was possible to establish bounds on the accident conditions with reasonable certainty.

2.1 ACCIDENT DATA ACQUISITION AND EVALUATION

The following sections present a discussion of the assumptions and considerations that form the basis for evaluating the 1974 to 1978 accident sample. Paragraph 2.1.1 describes the accident selection procedure, while paragraphs 2.1.2 and 2.1.3 cover the Evaluation Team approach and accident reconstruction methodology, respectively. The final paragraph, 2.1.4, discusses the statistical data sets that were analyzed in determining crash conditions.

2.1.1 ACCIDENT CASE SELECTION PROCEDURE. Original plans included examining accident records for a ten-year period. However, when the program began in March 1981, the most recent year for which records were available from the National Transportation Safety Board (NTSB) was 1978. A ten-year period would, therefore, have begun in 1969, and all participants in the program felt that the early years in that period would include a large number of aircraft types that no longer make up a significant percentage of aircraft in the civil operational fleet. In order to insure that a reasonably large percentage of current aircraft would comprise the sample, the most recent five-year period, 1974-78, was selected for investigation.

All records for rotorcraft accidents occurring during this period (a total of 1,351), were examined at the NTSB office in Washington, D.C. Copies of all reports containing accident site photographs or information describing the accident or events leading up to it, were obtained. Accident cases containing insufficient data to establish impact conditions or those pending litigation were deleted from the sample. Other cases were added when the manufacturers' files contained sufficient data for their inclusion. The resulting sample contained 311 accidents for the five-year period.

2.1.2 EVALUATION TEAM APPROACH. An Evaluation Team was established to analyze the available data for each accident. Simula Inc. personnel conducting the study were present for all accident evaluations to provide continuity in the reconstruction techniques used. Simula personnel provided expertise in determining human tolerance, in establishing the crash environment within the cockpit or cabin, and in using the techniques of accident reconstruction. Whenever possible, representatives of the manufacturer of the aircraft model involved participated in the evaluation effort. Three manufacturers, Bell Helicopter Textron, Inc., the Enstrom Helicopter Corporation, and Sikorsky Aircraft, participated in the Evaluation Team meetings for accidents involving their aircraft.

In all cases, these participants were able to provide specifics about the flight characteristics of the aircraft and, in some cases, structural capabilities of various aircraft components. Approximately 77 percent of the 311 accidents were evaluated with the aid of the manufacturers.

Personnel from the U.S. Army Safety Center, Fort Rucker, Alabama, participated in the evaluation effort for accidents involving aircraft models having military counterparts when the manufacturers were not able to support the program. These accidents accounted for approximately 10 percent of the samples. The remaining accidents were evaluated by Simula personnel.

2.1.3 EVALUATION METHODOLOGY. The goal of the Evaluation Team was to determine the conditions at impact, i.e., aircraft orientation and velocity for the principal impact*. These parameters primarily define the dynamics of the accident sequence, whereas accelerations transmitted to the occupant are functions of the crushing characteristics of the particular airframe. However, it was often useful to attempt to estimate acceleration levels in the aircraft in order to corroborate the most probable impact conditions.

An accident evaluation worksheet like that illustrated in figure 1, was completed for each accident. All categories in the upper block of the worksheet were completed from the original NTSB accident summary with the exceptions of survivability, crash environment, and aircraft attitude. These items were coded, and the lower narrative portions completed, during the Evaluation Team meetings. The codes used for completing the worksheets are listed in Appendix B.

Accidents were judged to be survivable or partially survivable according to the following definitions:

- Survivable - The acceleration environment was within the limits of human tolerance, and a sufficient occupiable volume remained for properly restrained (lap belt and shoulder harness) occupants, with the effects of fire not considered.

- Partially survivable - Some portion of the cockpit or cabin met the definition of survivable.

The assessment of survivability, as mentioned in the introduction to this section, implies that human tolerance to impact conditions is well defined. The basis for establishing human tolerance and the techniques for estimating the crash environment are discussed in the following paragraphs.

2.1.3.1 Human Tolerance. The tolerance of well-restrained seated occupants to whole-body acceleration is based on experimental studies of human volunteers, cadavers, and animals. Results of this work were compiled by Eiband (reference 10), and for this study were used as the basis for establishing survivable acceleration levels. Eiband's work is also summarized in the Aircraft Crash Survival Design Guide, Volume II, Chapter 4.0 (reference 2).

*Principal impact is defined as that which occurs when the majority of the decelerative forces were experienced and the most damage was sustained by the fuselage. The principal impact might not have been the initial impact.

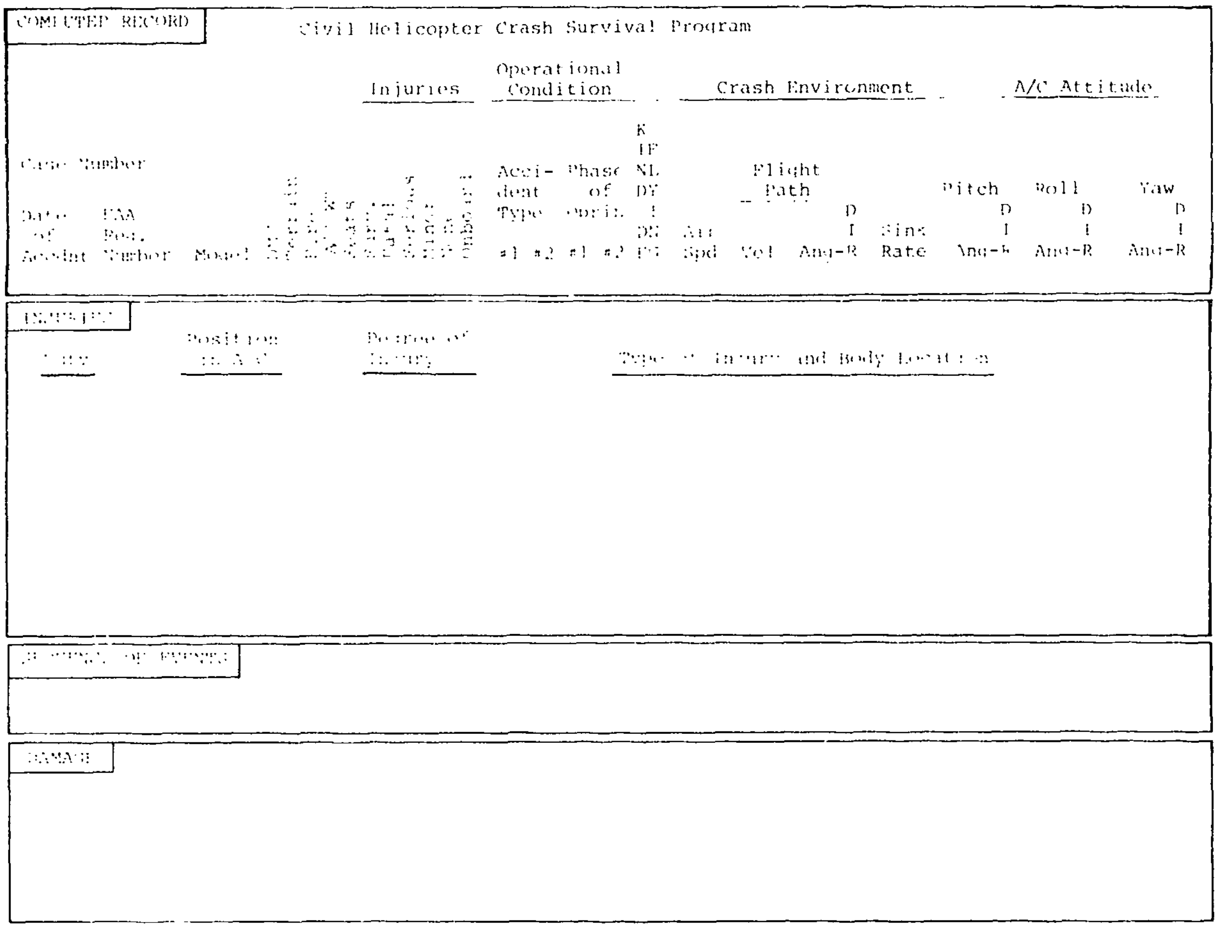


Figure 1. Accident evaluation worksheet.

It is generally assumed that tolerance to whole-body acceleration for occupants restrained by only a lap belt is lower than for an occupant with upper torso restraint. The lower tolerance is due to restraint loads being distributed over a smaller area and to spinal misalignment increasing localized loading in the spine. This issue was addressed as part of Task II and results are published in a separate report (reference 8). For Task I, as stated in the above definition of survivability, it was assumed that all occupants had the benefit of a lap belt and shoulder harness. This assumption was based on the belief that upper torso restraints are an effective approach to achieving occupant protection. Therefore, in accidents for models with lap-belt-only restraint systems, survivability was assessed on projected injuries and not necessarily the actual injuries received. Also, as noted, fire was not considered a factor in determining survivability.

Human tolerance to impact-type injuries as a result of striking an interior surface (secondary impact) has been thoroughly studied by the automotive community. Various force levels causing specific types of injuries can be estimated. However, for this study a definite criterion was used. Impact of extremities, unless extremely severe, was not considered a factor in survivability, but any impact of the head or upper torso was considered dangerous and possibly life threatening. If such trauma could have been prevented by proper restraint, then the accident was deemed potentially survivable.

2.1.3.2 Crash Environment. Techniques exist for reconstructing a crash environment from examination of aircraft wreckage, and these procedures are the subject of several educational courses (references 11 through 13). In theory, these procedures should be sufficient to estimate the magnitude of the impact parameters. Applied to this study, without the benefit of on-site investigation or comprehensive accident reports, the techniques were most useful for assessing relative severity among accidents.

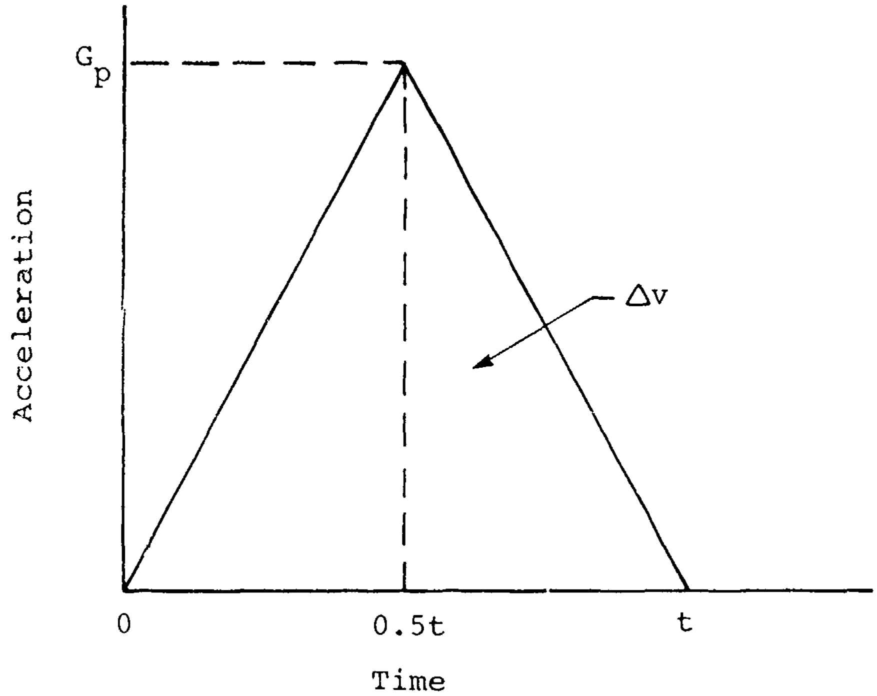
The procedure used in Task I was based on establishing with certainty, impact parameters (velocities, angles, acceleration levels) for a number of accidents. These accidents were then used as a reference in order to determine the severity of other, similar accidents. The following items were considered in analyzing the accidents that served as references:

- Investigator's report
- Photographs of aircraft and ground damage
- Pilot, passenger, and witness statements
- Injury descriptions (type, severity, and location in aircraft)
- Engineering analysis of component failures due to inertial overloading.

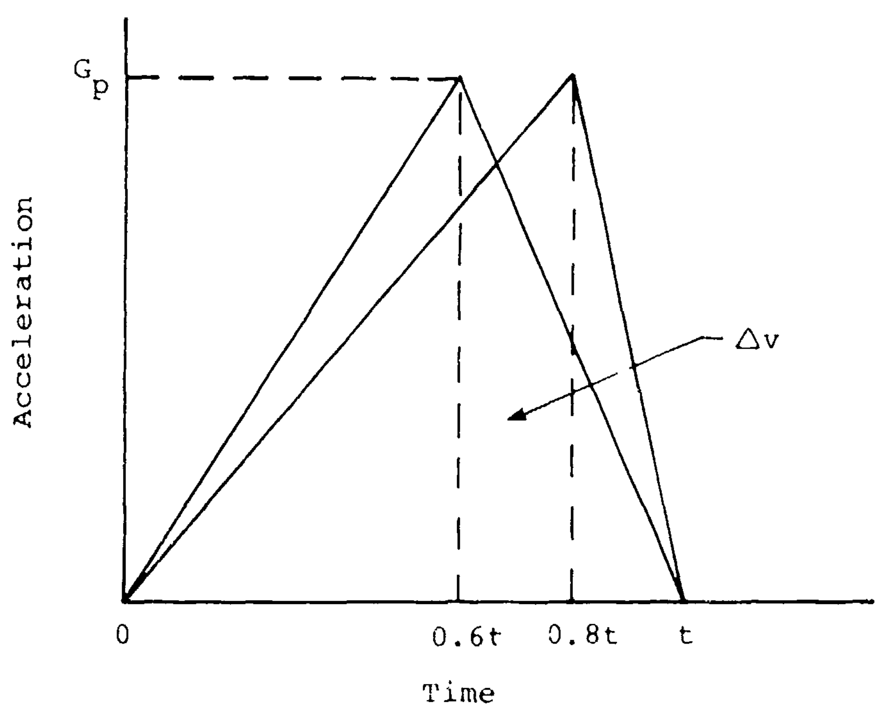
All of the accidents in the sample had, to some extent, the information described above. With this information it was possible to set limits on the most probable impact conditions by comparison with the referenced accidents.

As discussed in paragraph 2.1.3, it was often desirable to determine the acceleration environment for the occupants in order to relate severity levels to various injuries, or to reverse the procedure to aid in the determination of impact conditions based on injuries that occur at known levels. As an example, consider an accident of a small, two-place helicopter with primarily vertical impact forces in which both occupants received spinal fractures. Photographs of the monocoque seat pan structure revealed that several inches of vertical deformation occurred. Structural analysis of the seat failure load and the energy required to produce the deformation enabled the crash environment to be determined. The acceleration level determined in this manner corresponded with the levels required to produce spinal injury.

For evaluating the vertical component (with respect to the aircraft coordinate system) of the impact conditions, it was assumed that the acceleration-versus-time history had the shape of an equilateral triangle as shown in figure 2a. This assumption is based on measurements made in crash tests of helicopters and general aviation aircraft (references 14 through 16). The longitudinal component for accidents with significant downward pitch (nose impact with ground) was also assumed to have the equilateral triangular shape. However, a recent report analyzing crash tests of general aviation aircraft (reference 17) has indicated that the longitudinal pulse may be skewed slightly to the latter part of the pulse as shown in figure 2b. For accidents with a high longitudinal velocity at impact (e.g., run-on landing) it was assumed that the acceleration was essentially constant over the run-out distance, as shown in figure 3, unless the structure dug in or impacted some terrain feature.



a. Assumed vertical impact deceleration pulse shape.



b. Longitudinal impact deceleration pulse shapes (reference 17).

Figure 2. Triangular pulse shapes assumed to represent the impact deceleration environment in the principal impact.

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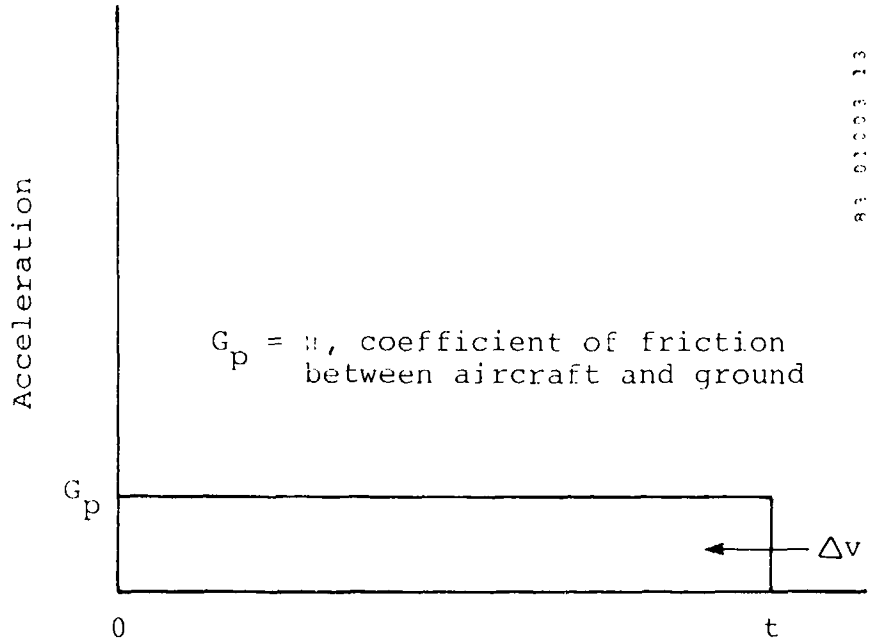


Figure 3. Constant acceleration-time history used to represent longitudinal acceleration for sliding aircraft.

The difference between "velocity at impact" (initial velocity) and "velocity change" needs to be considered when interpreting the data contained in this report. All velocities presented herein are initial velocities at the time of the principal impact. However, the energy contained in the impact pulse to which the aircraft structure is subjected during the principal impact is proportional to the velocity change, Δv. The magnitude of the acceleration that occurs during the velocity change determines the impact severity. It was assumed that, for the vertical component, there is very little rebound during impact, indicating that the initial velocity is approximately the same as the velocity change. However, in the longitudinal direction, a high initial velocity component may be present at impact with very little damage occurring until the aircraft structure "digs in" or impacts a rock or stump and thus causes an abrupt change in velocity. Results of this study indicate that high longitudinal velocities can be tolerated with little danger of injury providing no significant obstruction to sliding is encountered. It must be considered that reduction of velocity from the high initial value to zero occurs over a long time period with low average acceleration proportional to the coefficient of friction between the sliding aircraft and ground.

Formulas commonly used in accident reconstruction are shown in Appendix C, while Appendix D describes the Evaluation Team approach to determining the crash environment for an actual accident case.

2.1.4 <u>ACCIDENT DATA SAMPLES</u>. Data analyzed in Task I were divided into a number of subsets of the total sample to aid in interpretation of trends. Three different definitions of an "accident" were used, corresponding to definitions used in previous studies, in order to determine the effect on the cumulative

frequency of impact conditions. Also, the accident conditions were broken down according to four weight classes representing categories of capacity and operating conditions for the helicopters involved. These samples are described in the following sections.

2.1.4.1 Accident Definition. Three subsets of all accidents occurring during the 1974-78 evaluation period were examined to determine the effect of cumulative frequency of impact conditions. These subsets, based on accident severity, are defined below:

1. Total Sample - All accidents evaluated in the sample (311 accident cases).

2. Survivable - All accidents determined to be survivable or partially survivable according to the definition in paragraph 2.1.3 (211 accident cases).

3. Significant Survivable - All accidents determined to be survivable or partially survivable (154 accident cases) and meeting one or more of the following minimum injury or damage criteria:

   a. Postcrash fire - Occurrence of fire directly related to the impact forces.

   b. Personnel injuries - At least one injury of minor or serious category according to the NTSB coding system.

   c. Substantial structural damage - Damage to the aircraft structure which increases the hazard to the occupant through a reduction in occupiable volume or transmission of loads that would present a hazardous environment. Some examples are: Gross deformation of the fuselage structure, impingement of the cockpit by the rotor system, excessive vertical acceleration due to stiff underfloor or seat structure, or excessive impact energy resulting in structural compaction.

The significant survivable category corresponds to the definition used in developing the military helicopter crash environment described in references 2 and 18.

In the Interim Report (reference 9) submitted earlier in this program, a comparison was made between the distribution of impact velocities for the three categories of accidents. It was found that there was very little difference in velocity distributions among the three groups. The results from analysis of the significant survivable accident group were chosen for presentation in this report since the accidents in this group are those in which crashworthiness would be most effective.

2.1.4.2 Weight Classes. Accidents were examined in four categories corresponding to the maximum gross take-off weight of the helicopter involved. These classifications are shown in table 1 with the number of accidents that occurred for each class. Table 2 lists the aircraft models that fall into each weight class having accidents during the 1974-78 period.

TABLE 1. WEIGHT CLASSIFICATION FOR ACCIDENT EVALUATION

Weight Class	Maximum Gross Take-Off Weight (lb)	All Accidents 1974-78 No./Percent	Total Sample 1974-78 No./Percent
A	< 2,500	811 / 60.0	136 / 43.7
B	2,501 - 6,000	462 / 34.2	136 / 43.7
C	6,001 - 12,500	56 / 4.2	30 / 9.7
D	> 12,500	22 / 1.6	9 / 2.9
	TOTAL	1,351 /100.0	311 /100.0

TABLE 2. HELICOPTER MODELS EVALUATED BY WEIGHT CLASS

Weight Class	A	B	C	D
Maximum Gross Take-off Weight (lb)*	< 2,500	2,501-6,000	6,001-12,500	> 12,500
Manufacturer and Model	Bell 47 Brantly B-2 Enstrom F-28, 280 Hughes 300 (269)	Aerospatiale 315, 316, 318, 341, 350 Bell 206 Brantly 305 Hiller FH1100, UH-12 Hughes 500 (369) MBB BO 105	Aerospatiale SA306 Bell 204, 205, 212, 222 Sikorsky S-52, S-55, S-62	Aerospatiale SA330 Bell 214 Sikorsky S-58, S-64

*Estimated from Jane's All The World's Aircraft (reference 19).

2.1.4.3 Accident Data Subsets. The evaluation of each impact parameter, such as angle and velocity, was based on a set of accidents in which the particular parameter was known. Each set of accidents is actually a subset of the 311 accidents evaluated in this study. For each table or figure of statistical data, the accident sample size is specified. Note that in each case the size varies depending on the number of accidents in which the magnitude of the parameter of interest was known. Figure 4 shows the lineage of the major accident case subsets to aid in interpreting the data presented.

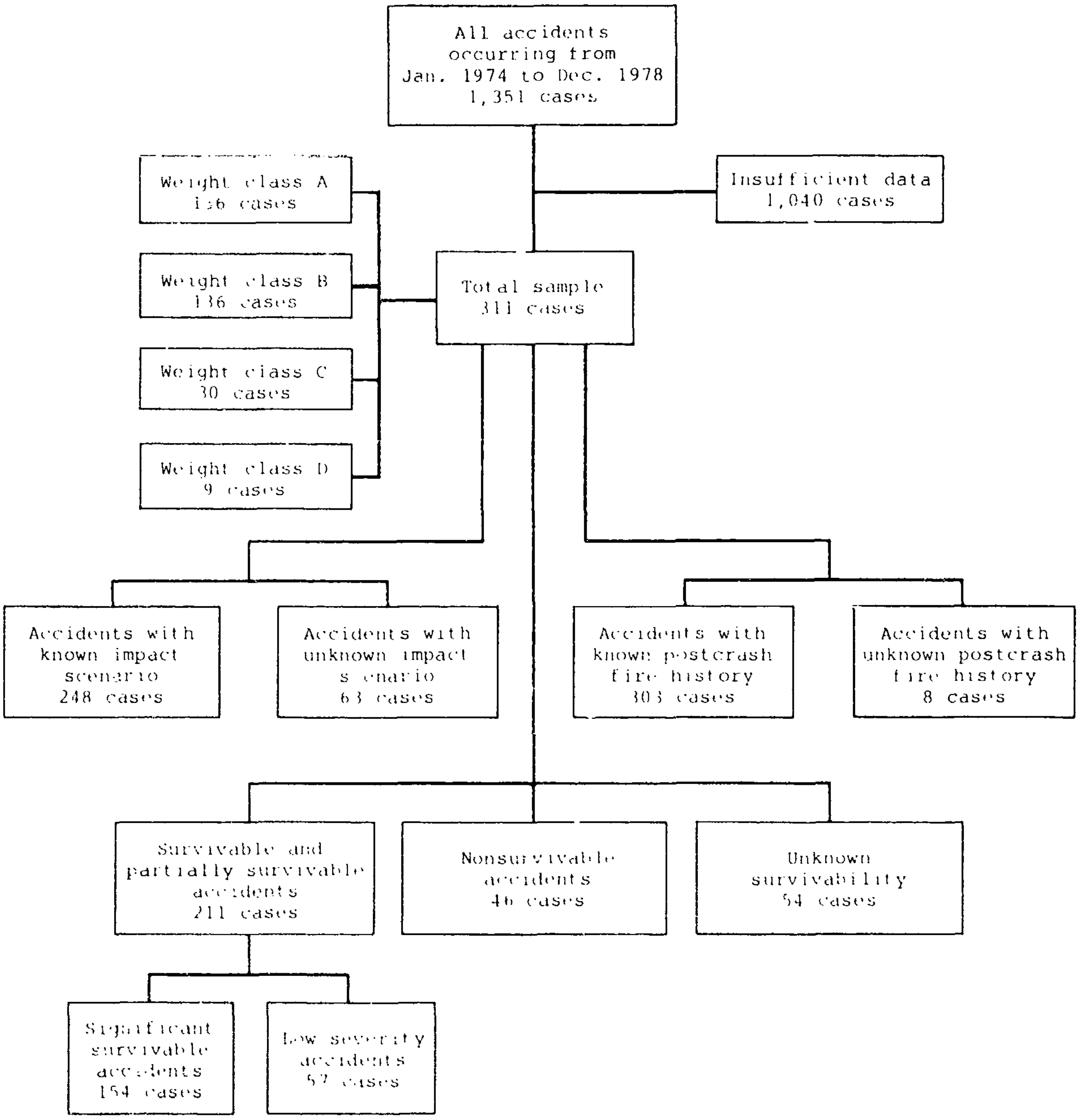


Figure 4. Relationship between accident sample subsets.

2.2 RESULTS OF DATA ANALYSES

Results of data analyses, in tabular and graphical form, are presented in the following four sections. In paragraph 2.2.1, characteristics of the accident sample are compared with the set of all helicopter accidents occurring during the 1974-78 period. Frequencies of aircraft attitude and velocity at impact are detailed in paragraphs 2.2.2 and 2.2.3, respectively. Finally, paragraph 2.2.4 presents graphs of various parameters related to impact severity, such as survivability, injury severity, and postcrash fire, with regard to impact velocity in order to develop envelopes defining survivable crash conditions.

2.2.1 ACCIDENT SAMPLE COMPARISON. This section presents a comparison between the accident sample chosen for evaluation and the set of all accidents occurring during the evaluation period. The parameters chosen for comparison include kind of flying, accident type, phase of operation, terrain at impact site, and injury severity. All of these parameters are tabulated in the standard Aircraft Accident Report (reference 20) and summaries of the data can be found in the Annual Review of Aircraft Accident Data, U.S. General Aviation (reference 21). These parameters were examined not only to understand the typical circumstances at the time of the accident, but also to determine if the evaluated accident sample had inherent biases, and if these biases would significantly influence the outcome of this study.

2.2.1.1 Kind of Flying. This parameter refers to the purpose for which the helicopter was being operated at the time of the accident. The four main categories are described below (taken from reference 22):

1. Instructional Flying

   Flying accomplished in supervised training under the direction of an accredited instructor.

2. Noncommercial Flying

   The use of an aircraft for purposes of pleasure, personal transportation or in connection with a private business, in corporate/executive operations, and in other operations wherein there is no direct monetary fee charged.

3. Commercial Flying

   All general aviation flying normally conducted for direct financial return, except instructional flying. It includes air taxi operations, aerial application, fire control, aerial mapping or photography, aerial advertising, power/pipeline patrol, and fish spotting.

4. Miscellaneous Flying

   Other kinds of flying not covered under the other three broad categories. In some instances, the criterion of direct financial return may or may not be present.

Table 3 shows the distribution, by percentage of the total accidents in the sample, of accidents occurring in each of the four major kinds of flying categories. The total sample compares favorably in terms of percentage distribution to all accidents in the 1974-78 period. Weight class A had a higher percentage of instructional and noncommercial accidents than the heavier weight classes. However, in all classes commercial operations were predominant.

2.2.1.2 Accident Type. Two accident types may be coded for each accident as described in the NTSB Aircraft Accident Report instructions (reference 22). The first accident type generally describes the condition that initiated the accident sequence. The second accident type, when used, describes the resulting situation following the first accident type. As an example, consider a

Kind of Flying	All Accidents 1974-78 (percent)	Total Sample 1974-78 (percent)	Weight Class A (percent)	Weight Class B (percent)	Weight Class C (percent)	Weight Class D (percent)
Instructional	10.2	8.9	15.4	4.3	3.3	0.
Noncommercial	25.3	18.8	24.3	17.4	0.	22.2
Commercial	49.3	55.0	39.7	65.2	76.7	55.6
Miscellaneous	15.2	17.3	20.6	13.1	20.0	22.2
Percentage of Total	100.0	100.0	100.0	100.0	100.0	100.0
Number of Accidents	1,351	311	136	136	30	9

TABLE 3. FREQUENCY OF ACCIDENT OCCURRENCE ACCORDING TO KIND OF FLYING CATEGORY

case in which engine fuel starvation occurs followed by a poorly executed autorotative landing resulting in aircraft damage. The first accident type for this example would be "engine failure or malfunction" and the second accident type would be coded as "hard landing." An accident in which a poorly executed power-on landing caused significant damage would generally be coded as a hard landing or ground collision with no second accident type.

Since not all accidents evaluated had two accident types coded, the first accident type was used for comparison of the samples. The most common first accident types are shown in table 4 as a percentage frequency of occurrence for all accidents in the sample. Other accident types occurred less frequently and were not included in the table. In general, the trends seen for all accidents occurring in the evaluation period follow through to the total sample and the individual weight classes.

2.2.1.3 Phase of Operation. The phase of operation coded on the accident report describes the flight status at the time of the accident and corresponds to the accident type. Therefore, there are two phases of operation coinciding with the two accident types. Five general categories are used to describe the phase of operation: static, taxi, take-off, inflight, and landing. Although there is a finer breakdown for each of these categories, only the five major phases were used for comparison of the samples. Table 5 shows the frequency of occurrence of accidents in each of these categories. The comparison uses the first phase of operation corresponding to the first accident type.

There is very close agreement in the accident percentages between all of the samples. More than half of the accidents were initiated while the aircraft were in flight, which includes normal cruise, climbing and descent, and hovering.

2.2.1.4 Terrain at Impact Site. The terrain type listed by accident investigators in the Aircraft Accident Report was, in most cases, an indication of the terrain in the general area of the accident and not necessarily that impacted. For developing crash scenarios, it was important to know the conditions to which the aircraft was subjected. Therefore, for this study, the terrain classification was expanded to include additional categories and allow inclusion of two terrain codings corresponding to the actual impacted terrain. As an example, consider the following case: engine failure necessitates an

TABLE 4. FREQUENCY OF OCCURRENCE OF PREDOMINATE FIRST ACCIDENT TYPES

Accident Type	All Accidents 1974-78 (percent)	Total Sample 1974-78 (percent)	Weight Class A (percent)	Weight Class B (percent)	Weight Class C (percent)	Weight Class D (percent)
Hard landing	8.5	6.7	10.3	4.3	0.	11.1
Rollover	7.2	6.7	3.7	11.6	0.	0.
Collision with Ground/Water	16.2	15.4	10.3	19.6	15.6	22.2
Collision with Wires/Poles	9.4	9.6	16.9	4.3	3.1	0.
Collision with Trees	3.2	4.2	2.2	5.1	6.2	11.1
Airframe Failure in Flight	3.4	3.8	4.4	3.6	3.1	0.
Engine Failure or Malfunction	30.4	27.2	26.5	29.0	18.8	33.3
Tail Rotor Failure	6.1	9.0	10.3	6.5	15.6	22.2
Main Rotor Failure	3.0	3.8	2.2	3.0	9.4	0.
Other	12.6	13.6	13.2	13.0	28.2	0.1
Percentage of Total	100.0	100.0	100.0	100.0	100.0	100.0
Number of Accidents	1,351	311	136	136	30	9

TABLE 5. FREQUENCY OF PHASE OF OPERATION CORRESPONDING TO FIRST ACCIDENT TYPE

Phase of Operation	All Accidents 1974-78 (percent)	Total Sample 1974-78 (percent)	Weight Class A (percent)	Weight Class B (percent)	Weight Class C (percent)	Weight Class D (percent)
Static	2.3	1.3	0.7	2.3	0.	0.
Taxi	3.0	2.9	3.0	3.7	0.	0.
Take-off	17.7	15.3	12.6	17.9	13.8	22.2
Inflight	55.0	58.0	60.7	53.0	62.1	77.8
Landing	22.0	22.5	23.0	23.1	24.1	0.
Percentage of Total	100.0	100.0	100.0	100.0	100.0	100.0
Number of Accidents	1,351	311	136	136	30	9

autorotative landing. The pilot attempts to clear a heavily wooded area, and as a result of low rotor RPM, a hard landing occurs on a frozen, rock-covered field. The accident investigator may have coded the terrain type as "trees" due to the wooded area. For this study, the terrain codes actually used would be "frozen" and "rocky." This is an important distinction for design considerations because the ground, in this case, would not have provided any cushioning and the presence of rocks may have impeded the ability of the landing gear to function effectively.

Table 6 shows the frequency of terrain types at the impact site for the evaluated accidents. Because of the changes in the coding procedure, a meaningful comparison could not be made between the evaluated accidents and all accidents occurring during the evaluation period. Note that the cumulative percentage of terrain types is greater than 100 percent because two types could be used for each accident.

The data in table 6 indicate that approximately 40 percent of the accidents occur on level, flat ground. For design purposes, a number of terrain categories can be combined that include similar impact conditions. Table 7 shows a grouping of the predominate terrain conditions for each accident that will be more useful for developing design scenarios.

The terrain classification is useful for determining the conditions in which the energy absorption capability of the landing gear could be utilized to absorb crash energy. From the predominate terrain types listed in table 7, the gear could function on impact (within the limits of aircraft orientation) for the following terrain types: soft, prepared surface, and frozen. Accidents occurring on this terrain account for 62.3 percent of the total. A review of the survivable accidents in the sample indicated that the landing gear functioned to some degree to lessen impact severity in 53 percent of the cases. The reduction in number of accidents in which the gear actually function is primarily due to the effect of aircraft orientation at impact.

2.2.1.5 Injury Severity. The distribution of injuries occurring at various severity levels was also used for comparing the evaluated sample to all accidents occurring in the sample period. Table 8 lists the percentage of occupants receiving injuries of a specified severity level, as well as those who were uninjured.

The data in table 8 indicate that a greater percentage of the occupants in the total sample received fatal or serious injuries than did those in the all accidents sample. This would indicate that the evaluated sample contained a disproportionate number of severe accidents. The original investigative procedures contributed to this bias because the investigator was more likely to spend a greater amount of time documenting the circumstances of a fatal or severe crash than one with very little damage or injury. As a result, the severe and fatal accident reports filed at NTSB, when there were data available, tended to contain more useful information for the evaluation effort.

The bias in the severity of accidents contained in the total sample will have some effect on the results of analyses based on cumulative percentage of a parameter. The cumulative frequency of vertical impact velocity, which is based on the percentage of accidents that occur with a vertical velocity component at or below a specified level, is an example of a parameter that will be affected. However, paragraph 2.2.4 presents an analysis of survivability and injury severity data that can be used to establish envelopes for survivable conditions not affected by the sample bias discussed above.

2.2.2 IMPACT ATTITUDE. The aircraft attitude at the time of the major impact was determined by examining the structural damage in each quadrant of the airframe, from occupant injury patterns at various locations in the aircraft, and from knowing the phase of flight. The aircraft attitude is described as angular

TABLE 6. FREQUENCY OF TERRAIN CLASSIFICATION AT ACCIDENT IMPACT SITE

Terrain Classification	Total Sample 1974-78 (percent)	Weight Class A (percent)	Weight Class B (percent)	Weight Class C (percent)	Weight Class D (percent)
Mountainous	12.5	8.8	14.5	20.0	11.1
Hilly	8.9	8.8	8.7	10.0	11.1
Rolling	6.7	5.9	8.7	3.3	0.
Level, Flat	39.0	50.7	27.5	33.3	55.5
Frozen	2.9	0.7	5.8	0.	0.
Rocky	4.8	6.6	3.6	3.3	0.
Sandy	2.0	2.2	1.5	0.	11.1
Trees	17.6	16.2	17.4	16.7	44.4
City Area	3.8	5.9	2.9	0.	0.
Plowed	5.1	9.6	1.5	3.3	0.
Water	11.2	5.9	13.8	23.3	11.1
Sloped	2.2	3.7	1.5	0.	0.
Snow	2.2	2.2	1.5	3.3	11.1
Paved	8.0	8.8	7.2	10.0	0.
Offshore Rig	1.0	0.	2.2	0.	0.
Soft	10.2	9.6	11.6	6.7	11.1
Other	1.6	1.5	1.5	3.3	0.
Unknown	2.2	1.5	3.6	0.	0.
TOTAL	141.9	148.6	135.0	136.5	166.5
Number of Accidents	311	136	136	30	9

TABLE 7. DISTRIBUTION OF MAJOR TERRAIN TYPES FOR 311 ACCIDENTS IN THE TOTAL SAMPLE (1974-78)

Terrain Type	Description	Percentage of Impacts
Soft	Soft, sandy, plowed	40.1
Vegetation	Contact with trees, large shrubs	15.9
Uneven Ground	Rocks, stumps, logs	8.6
Prepared Surface	Paved, hard dirt, gravel	17.9
Water		11.3
Snow		1.3
Frozen	Frozen ground, ice	4.3
Offshore Rig		0.6
		100.0

TABLE 8. FREQUENCY OF OCCURRENCE OF INJURY SEVERITY

Injury Severity	All Accidents* 1974-78 (percent/No.)	Total Sample 1974-78 (percent/No.)	Weight Class A (percent/No.)	Weight Class B (percent/No.)	Weight Class C (percent/No.)	Weight Class D (percent/No.)
Fatal	11.2/308	22.6/171	29.1/74	16.8/59	27.7/36	10.5/2
Serious	10.4/286	13.4/101	16.5/42	10.5/37	10.8/14	42.1/8
Minor	18.3/[illegible]	21.3/161	16.9/43	23.3/82	25.4/33	15.8/3
None	60.1/1,653	42.7/322	[illegible]/95	49.4/174	36.1/47	31.6/6
TOTAL	100.0/2,750	100.0/755	100.0/254	100.0/352	100.0/130	100.0/19

*Source: NTSB Annual Review of Aircraft Accident Data for 1974 to 1978 (reference 21).

deviations from the neutral pitch, roll, and yaw axes which are shown in figure 5. This section presents tables listing the distribution of pitch, roll, and yaw angle for the total sample. The angle distributions for the individual weight classes are presented in Appendix E.

The impact attitude data were developed based on the total sample of 311 accidents. It was not possible to determine the pitch, roll, or yaw angle for every accident. Therefore, there are a significant number of accidents listed as "unknown" in the angle distributions.

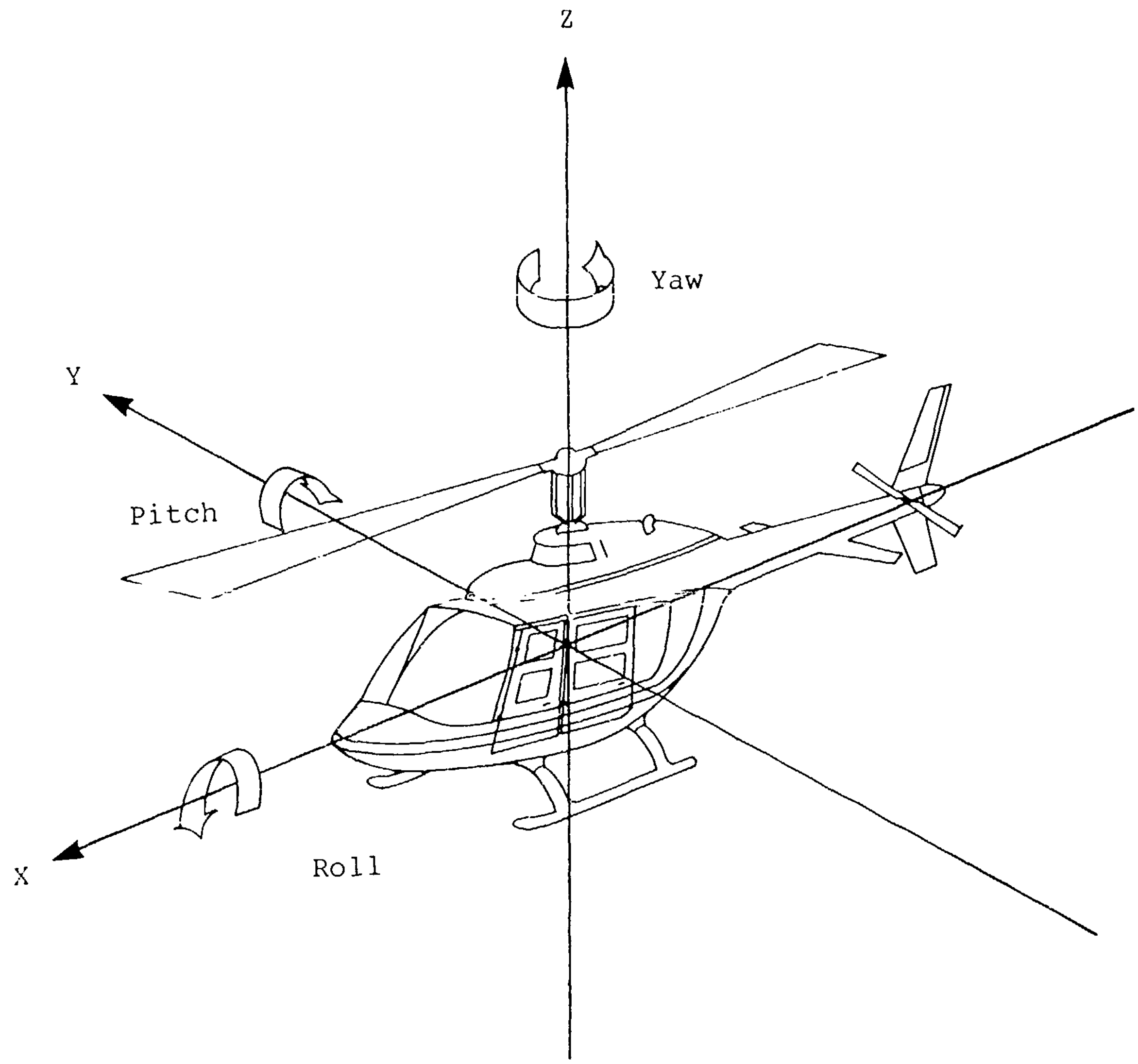


Figure 5. Aircraft coordinate and attitude directions.

2.2.2.1 Pitch Angle Distribution. The distribution of pitch angle for the total sample is shown in table 9. In approximately one-third of all of the accidents in which pitch angle could be determined, the aircraft was level at impact. There is a higher incidence of impacts with a nose-up attitude (positive pitch angle) than nose-down. This is mainly due to the significant number of accidents that occur while attempting to reduce the airspeed and sink rate with excessive flaring.

Seventy-one percent of all accidents had a pitch angle between -10 and +10 degrees, and the ±20-degree interval includes 87 percent of all accidents.

2.2.2.2 Roll Angle Distribution. The roll attitude distribution for all aircraft is listed in table 10. There was some indication in the data that the roll direction had a higher frequency toward the pilot's side of the aircraft. However, the position that the pilot occupies varies among helicopter models, and on the average, the distribution of roll angles was symmetric about the neutral position (zero degrees).

TABLE 9. DISTRIBUTION OF PITCH ANGLE AND DIRECTION AT IMPACT FOR THE TOTAL SAMPLE (311 ACCIDENTS).

Angle (Deg)	No. of Accidents Per Direction Up	Level	Down	Total Accidents	Percent of Total	Cumulative Percent
0		69		69	32.1	32.1
1-10	57		27	84	39.1	71.2
11-20	20		13	33	15.4	86.6
21-30	3		7	10	4.6	91.2
31-45	1		5	6	2.8	94.0
46-60	1		2	3	1.4	95.4
61-75	0		0	0	0	95.4
76-90	0		2	2	0.9	96.3
91-120	0		2	2	0.9	97.2
121-150	0		3	3	1.4	98.6
151-180	0		3	3	1.4	100.0
Total Accidents with Known Pitch Angle				215	100.0	
Accidents with Unknown Pitch Angle				96		
			TOTAL	311		

The data in table 10 indicate that almost two-thirds of the accidents occur in the level position, with 72 percent occurring within ±10 degrees and 80 percent within ±20 degrees. The grouping of accidents in the 76- to 90-degree interval includes most rollovers.

Roll angle is one of the critical parameters for landing gear design. The distribution of vertical impact speed at various roll angles will have the greatest influence on the design. A discussion of the relationship between vertical impact speed and roll angle as related to landing gear is presented in paragraph 2.2.5.

2.2.2.3 Yaw Attitude. The yaw angle was the most difficult impact parameter to estimate. In many accidents where there was a loss of directional control, the aircraft impacted with a significant yaw angle and, in many cases,

TABLE 10. DISTRIBUTION OF ROLL ANGLE AND DIRECTION AT IMPACT FOR THE TOTAL SAMPLE (311 ACCIDENTS)

Angle (Deg)	No. of Accidents Per Direction: Right	Level	Left	Total Number	Percent of Total	Cumulative Percent
0		133		133	61.0	61.0
1-10	12		13	25	11.5	72.5
11-20	6		11	17	7.8	80.3
21-30	2		2	4	1.8	82.1
31-45	0		6	6	2.8	84.9
46-60	0		0	0	0	84.9
61-75	0		0	0	0	84.9
76-90	16		5	21	9.6	94.5
91-120	2		1	3	1.4	95.9
121-150	0		1	1	0.5	96.4
151-180	8		0	8	3.6	100.0
Total Accidents With Known Roll Angle				218	100.0	
Accidents with Unknown Roll Angle				93		
			TOTAL	311		

a large yaw rate. The magnitude of these parameters was very difficult to estimate from the accident description and damage photographs. The yaw angle distribution for accidents in which an estimate of the yaw magnitude could be made is given in table 11. An estimate could not be made in the remaining accidents; however, in a significant number of these accidents it was known that the yaw angle was large. Because of the difficulty in estimating yaw angle, a scenario was developed (see paragraph 2.3.1) for accidents with high yaw rates and angles. The relative severity of this class of accidents is compared to the other scenario types in paragraph 2.3.2.

TABLE 11. DISTRIBUTION OF YAW ANGLE AND DIRECTION AT IMPACT FOR THE TOTAL SAMPLE (311 ACCIDENTS)

Angle (Deg)	No. of Accidents Per Direction Right	Level	Left	Total Number	Percent of Total	Cumulative Percent
0		147		147	78.1	78.1
1-10	13		7	20	10.6	88.7
11-20	1		4	5	2.7	91.4
21-30	2		0	2	1.1	92.5
31-45	1		1	1	0.5	93.0
46-60	2		0	2	1.1	94.1
61-75	2		0	2	1.1	95.2
76-90	4		1	5	2.7	97.9
91-120	1		0	1	0.5	98.4
121-150	0		2	2	1.1	99.5
151-180	1		0	1	0.5	100.0
Total Accidents with Known Yaw Angle				188	100.0	
Accidents with Unknown Yaw Angle				123		
			TOTAL	311		

2.2.3 <u>IMPACT VELOCITY</u>. Impact velocity was estimated in intervals in a similar manner to the impact angles, and as described in Appendix B. Three velocity components were used, each calculated in the aircraft coordinate system as shown in figure 5. Frequency distribution histograms are presented for each component, with various segments of the evaluated sample indicated, such as nonsurvivable, low severity, and significant survivable accidents. The low severity group includes accidents that were survivable, yet did not meet the minimum injury, damage, or fire criteria of the significant survivable subset. Also, this section includes cumulative frequency curves for each velocity component. The 95th-percentile velocity is included with each of the cumulative frequency plots for use in comparing these data to similar military helicopter accident data. Velocity distribution histograms for each of the four weight classes are presented in Appendix F.

2.2.3.1 Vertical Impact Velocity. The frequency distribution of the vertical velocity component for all aircraft is shown in figure 6. The distribution for the total sample is indicated by the total height of each column which is proportional to the percentage of accidents with the indicated velocity. The survivable sample distribution would be the height of each column minus the nonsurvivable segment. The significant survivable accident sample corresponds to the column height without the nonsurvivable and low-severity accidents.

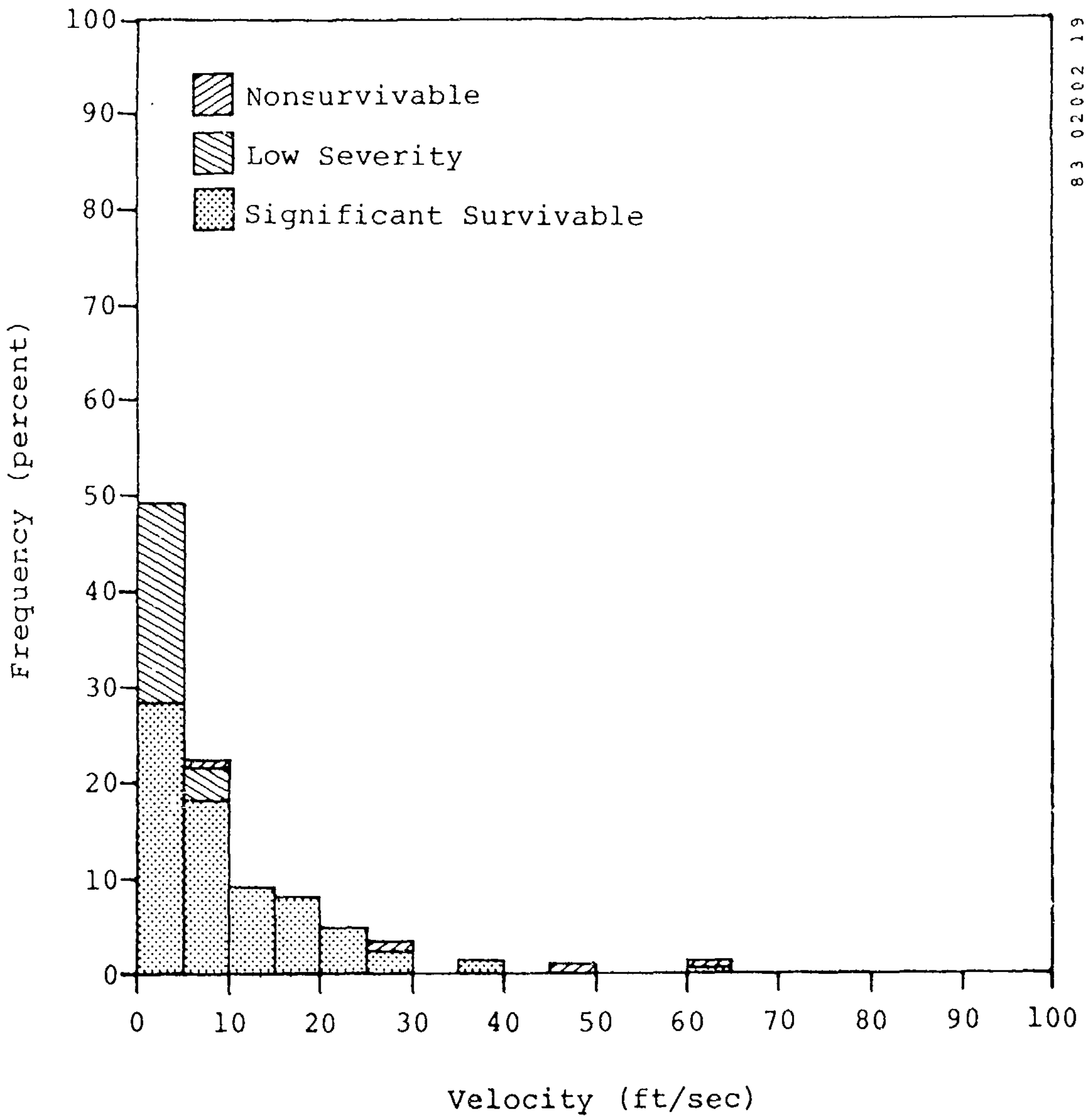


Figure 6. Frequency of occurrence of vertical impact velocity, total sample (195 accidents out of 311 with known vertical impact velocity).

The numerical data used in developing figure 6 are listed in table 12 in a cumulative percentage format. These data are useful for developing cumulative frequency plots such as that shown in figure 7.

TABLE 12. CUMULATIVE FREQUENCY OF OCCURRENCE OF VERTICAL VELOCITY FOR ALL WEIGHT CLASSES

Velocity (ft/sec)	Total Sample 1974-78 (percent)	Survivable Accidents (percent)	Significant Survivable Accidents (percent)
0-5	49.2	51.1	39.3
6-10	71.3	73.4	64.3
11-15	80.0	82.5	76.4
16-20	88.2	91.0	87.9
21-25	92.8	95.7	94.3
26-30	96.4	97.9	97.1
31-35			
36-40	98.0	99.5	99.3
41-45			
46-50	99.0		
51-55			
56-60			
61-65	100.0	100.0	100.0
No. of Accidents with Known Vertical Velocity	195	188	140
No. of Accidents with Unknown Vertical Velocity	116	23	14
TOTAL	311	211	154

The 95th-percentile levels of vertical velocity established in this study were 28, 24, and 26 ft/sec for the total sample, for survivable accidents, and for significant survivable accidents, respectively. As design requirements, the U.S. military uses the 95th-percentile level of velocity components, based on an accident sample similar to the significant survivable set. The accident studies used to establish these levels were conducted in the 1960's (reference 23). The

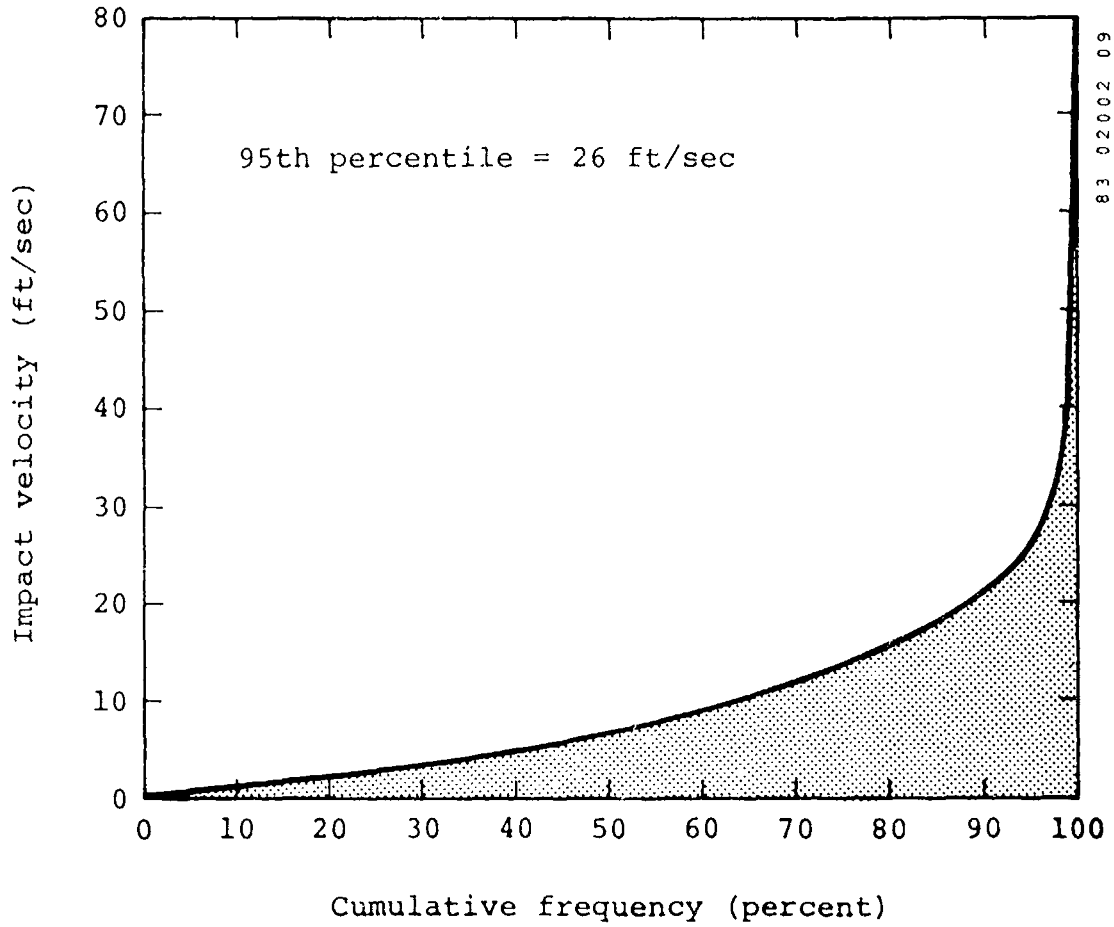


Figure 7. Cumulative frequency of occurrence of vertical impact velocity, significant survivable accidents.

current U.S. Army 95th-percentile vertical velocity design goal is 42 ft/sec. However, a recent study of landing gear design and test criteria for the U.S. Army (reference 24) indicates that the actual 95th-percentile survivable vertical velocity change seen in recent accidents (1975-1980) may be closer to 30 ft/sec.

2.2.3.2 Longitudinal Impact Velocity. The longitudinal impact velocity histogram is presented in figure 3 for the total sample. The data for the cumulative frequency analyses for the three sample sets are presented in table 13. The corresponding cumulative frequency plot for the significant survivable sample is shown in figure 9.

The cumulative frequency plot indicates that the 95th-percentile level is 50 ft/sec. For comparison, the U.S. Army design requirement is also for 50 ft/sec in the longitudinal direction.

2.2.3.3 Lateral Impact Velocity. The lateral impact velocity histogram is presented in figure 10. The problems with estimating yaw angle, discussed previously in paragraph 2.2.2.3, presented the same type of problem with estimating lateral velocity, since this component is based on flight path velocity

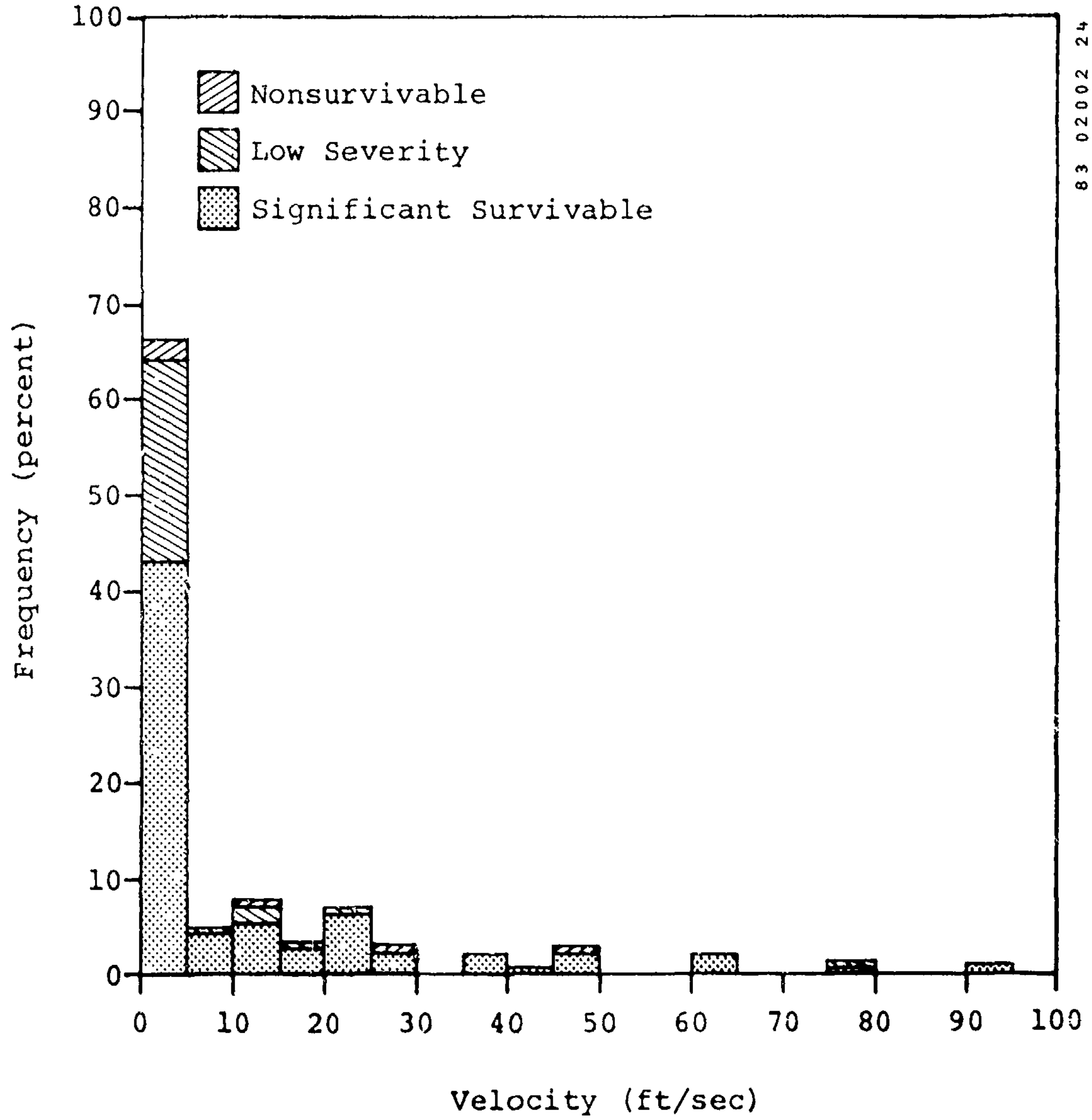


Figure 8. Frequency of occurrence of longitudinal impact velocity, total sample (190 accidents out of 311 with known longitudinal impact velocity).

and yaw angle. However, in most cases in which the yaw angle was large, the accompanying flight path velocity was small, resulting in a low lateral velocity. Therefore, it is believed that the cumulative distribution shown in figure 10 is representative.

The cumulative frequency of lateral velocity for all aircraft is presented in figure 11. The curve indicates that the 95th-percentile level is 10 ft/sec. It should be noted that for a run-on crash sequence with slide-out, the lateral velocity is not greatly threatening to the occupant. The conditions under which the aircraft rolls over or impacts a rigid obstacle in flight are much more serious. This was considered in developing the recommended design criteria.

TABLE 13. CUMULATIVE FREQUENCY OF OCCURRENCE OF LONGITUDINAL VELOCITY FOR ALL WEIGHT CLASSES

Velocity (ft/sec)	Total Sample 1974-78 (percent)	Survivable Accidents (percent)	Significant Survivable Accidents (percent)
0	0.	0.	0.
5	65.8	66.3	60.0
10	70.5	71.2	65.7
15	77.9	78.3	73.0
20	81.1	81.5	76.6
25	87.9	88.6	85.4
30	90.5	90.8	88.3
35			
40	92.6	92.9	91.2
45	93.2	93.5	92.0
50	95.8	95.7	94.9
55			
60			
65	97.9	97.8	97.8
70			
75			
80	99.0	98.9	98.5
85			
90			
95	100.0	100.0	100.0
No. of Accidents with Known Longitudinal Velocity	190	183	137
No. of Accidents with Unknown Longitudinal Velocity	121	28	17
TOTAL	311	211	154

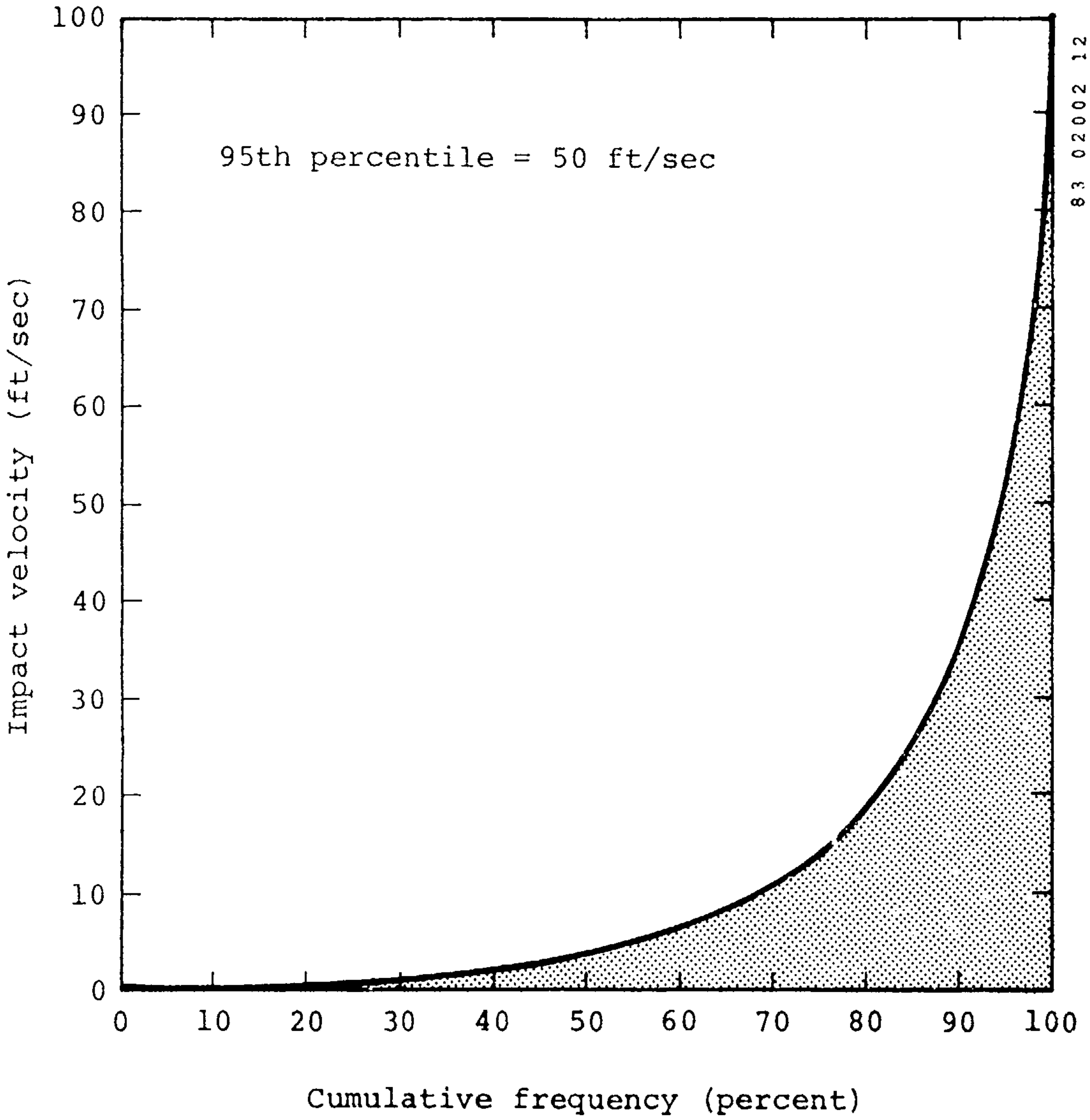


Figure 9. Cumulative frequency of occurrence of longitudinal impact velocity, significant survivable accidents.

2.2.4 VELOCITY COMPONENT CORRELATIONS. The previous sections in this chapter have been devoted to tabulations of the individual velocity and angle components. These parameters aid in understanding the most severe environment that the existing aircraft can withstand and the occupant survive. However, this type of analysis provides little information about typical impact and survivability conditions for an off-axis impact, i.e., when the impact velocity is not directed along the aircraft x, y, or z axis. This section considers the interrelationship of various velocity components and their effect on survivability-related factors.

Evaluation of each accident provided an estimate of the magnitude of the three velocity components and a determination of the survivability of the impact conditions. It would be possible to plot the impact velocity components for each

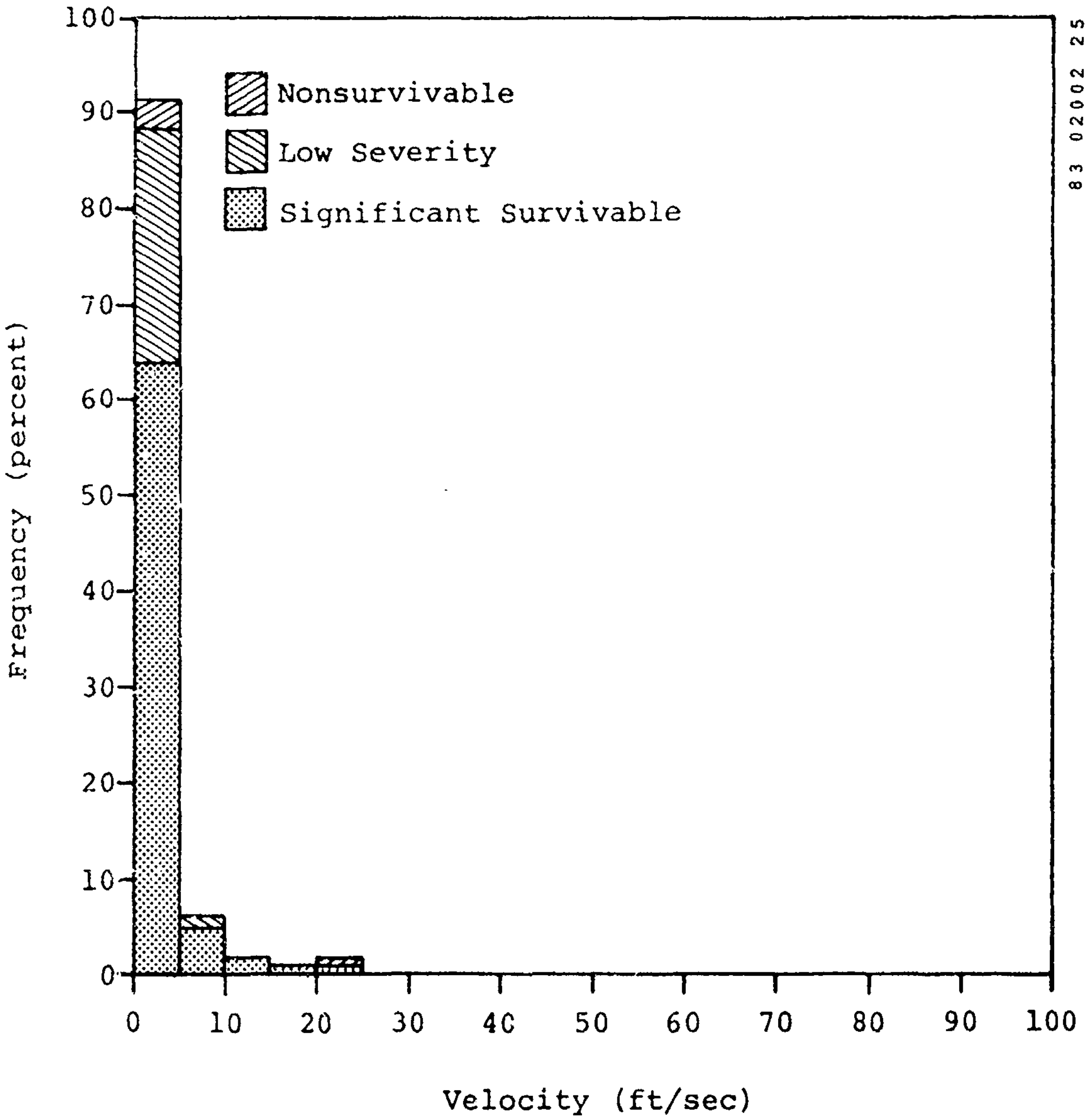


Figure 10. Frequency of occurrence of lateral impact velocity, total sample (189 accidents out of 311 with known lateral impact velocity).

accident on a three-dimensional graph. Coding the survivability for each accident point would permit construction of an envelope of survivable velocity combinations. The obvious problem with three-dimensional graphs is the difficulty in displaying the position of individual points. In this section, two-dimensional plots are used to show the accident distribution according to the magnitude of individual velocity components.

2.2.4.1 Survivability Envelopes. Three graphs are presented, figures 12, 13, and 14, showing the accident distribution according to velocity components and survivability. The longitudinal-vertical velocity distribution shown in figure 12 is the most informative, because these two components are generally much larger than the lateral component.

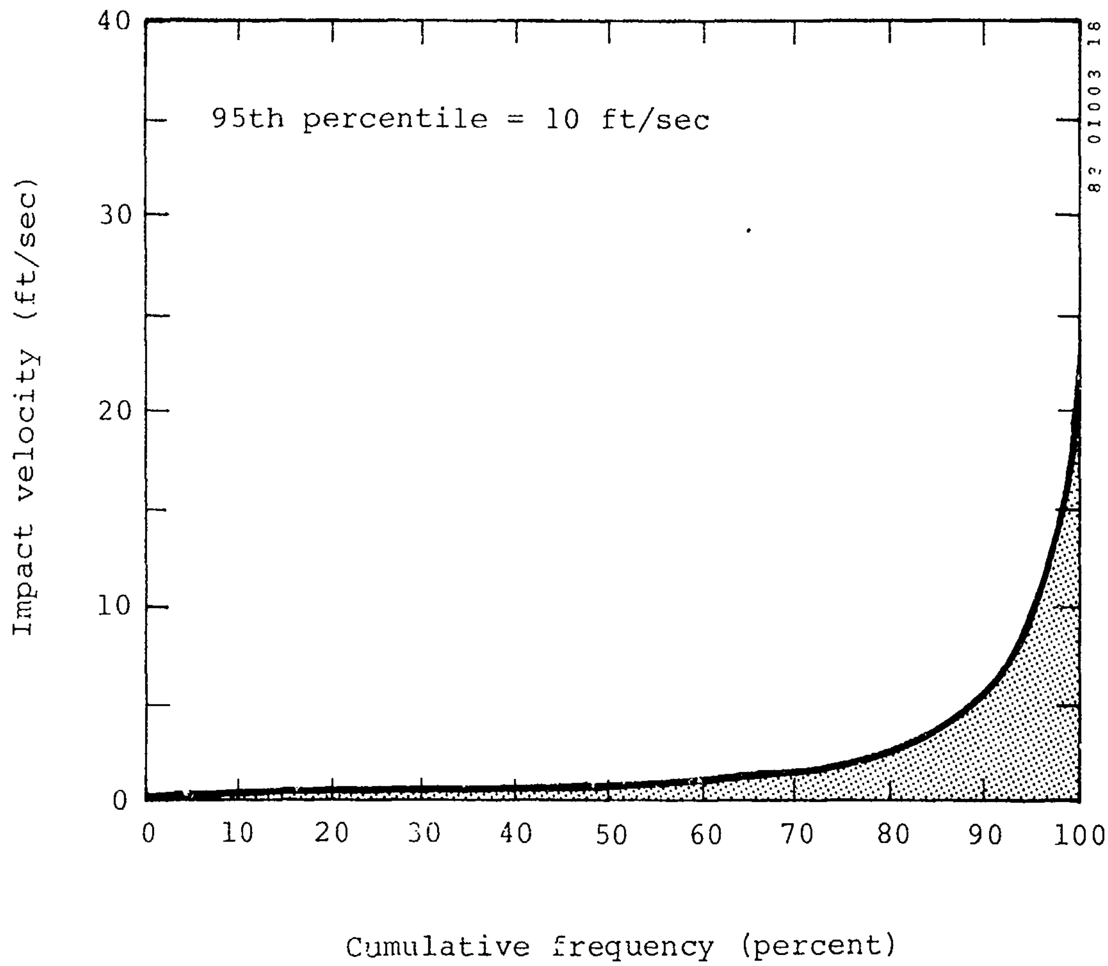


Figure 11. Cumulative frequency of occurrence of lateral velocity, significant survivable accidents.

In each of these figures, an ellipsoidal surface is used to represent the locus of maximum velocities that appear to be survivable or partially survivable. The intercept on each of the axes coincides with an accident having a unidirectional velocity component; these intercepts are the same as the 95th-percentile components determined in paragraph 2.2.3 for the significant survivable sample. These curves provide an indication of the survivable conditions for impacts with velocity components in more than one direction. Also presented are envelopes describing the 95th-percentile level of all evaluated accidents (survivable, partially survivable, and nonsurvivable).

2.2.4.2 Injury Envelopes. The graphs presented in the previous section use survivability as the index for determining the maximum tolerable impact velocities. Injury severity can also be used as the index to determine tolerable conditions. Using injury severity to code the accidents on a velocity component graph gives an indication of typical levels producing injuries of various severities. It becomes much easier to assess the tolerable conditions as increasing velocities produce injuries that change from minor to severe and finally fatal.

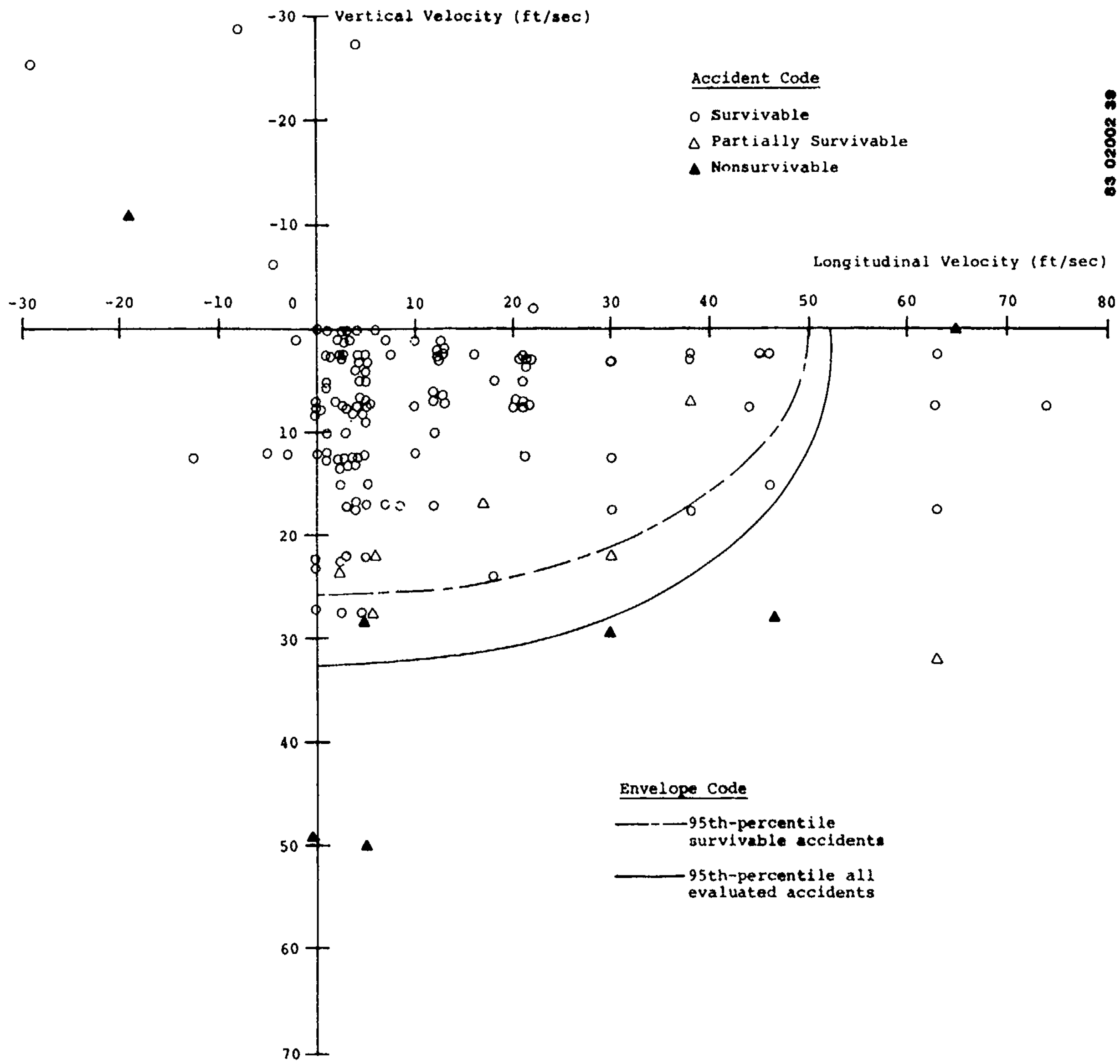


Figure 12. Accident survivability for longitudinal-vertical impact velocity components.

The first graph of this type, for the longitudinal-vertical velocity components with lap-belt-only restraint, is shown in figure 15. An envelope of these accidents indicates that 18 ft/sec pure vertical and 23 ft/sec pure longitudinal impact speeds are the levels at which the injuries are consistently severe or fatal. Figure 16 is a plot of injury conditions for occupants restrained with a lap belt and shoulder harness (some type of upper torso restraint). The vertical impact level (i.e. in the aircraft vertical axis) which consistently produced severe or fatal injuries was approximately 23 ft/sec, which is significantly higher than the velocity range in the lap-belt-only condition. However, for mainly longitudinal-type impacts, no serious or fatal injuries were found in the sample, even at very high velocities. This indicates that an upper torso restraint is effective in preventing the secondary, impact-type injuries (head and torso strikes) that are common in longitudinal impacts with small

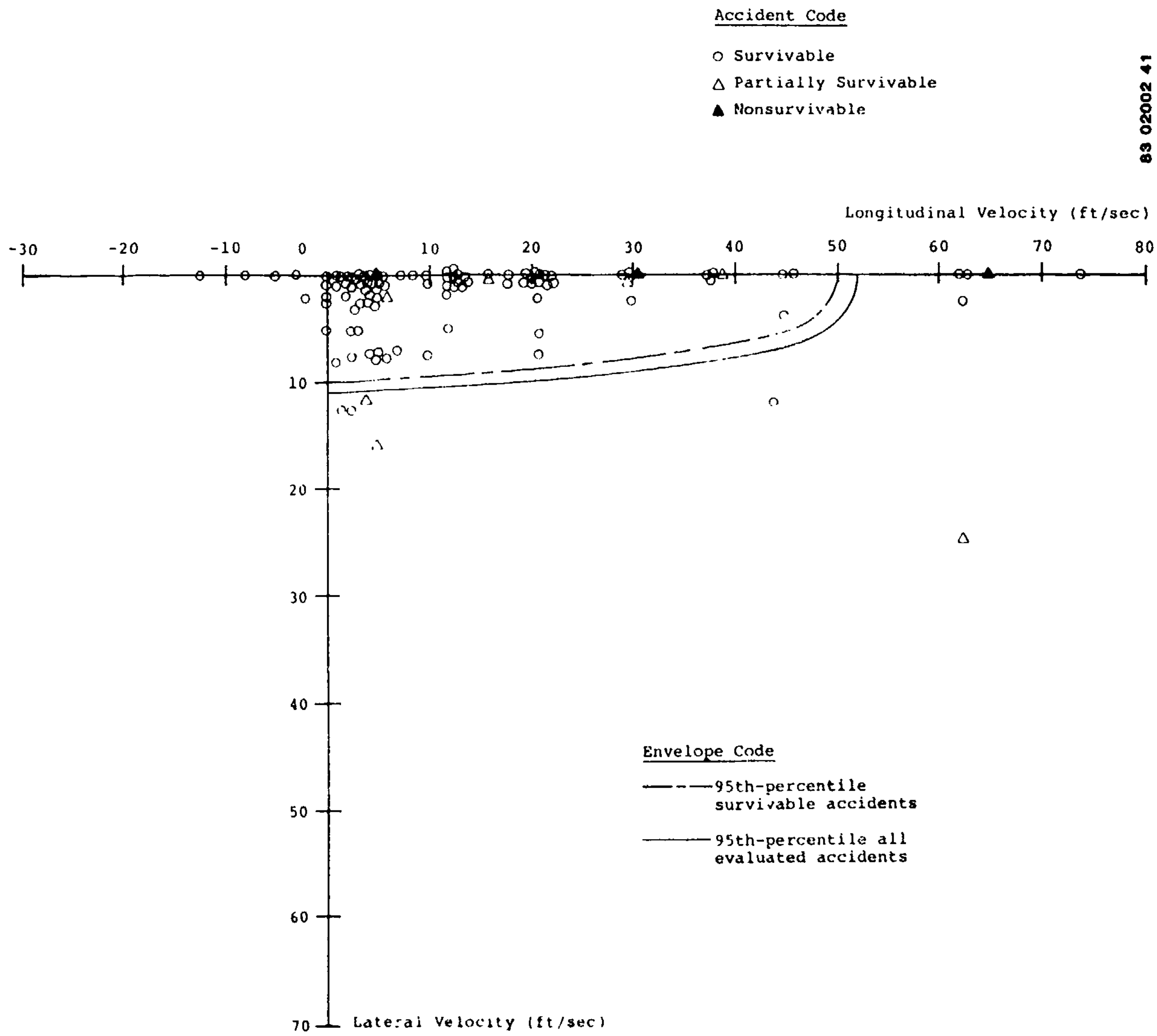


Figure 13. Accident survivability for longitudinal-lateral impact velocity components.

aircraft. Upper torso restraints may also have slightly increased the tolerable vertical impact conditions. This type of injury is a function of the acceleration levels experienced by the occupant and is influenced by spinal posture and the axial-load-bearing capability of the vertebral bodies. References 2 and 8 suggest that upper torso restraint may help to maintain a proper spinal alignment to resist vertical loading.

2.2.4.3 Postcrash Fire Envelope. Postcrash fire* was also analyzed with respect to the impact velocity components. Figure 17 shows the distribution

*During the accident evaluation phase, inflight and postcrash fires were noted. However, only fires initiated on impact were considered pertinent to the development of crashworthy design conditions.

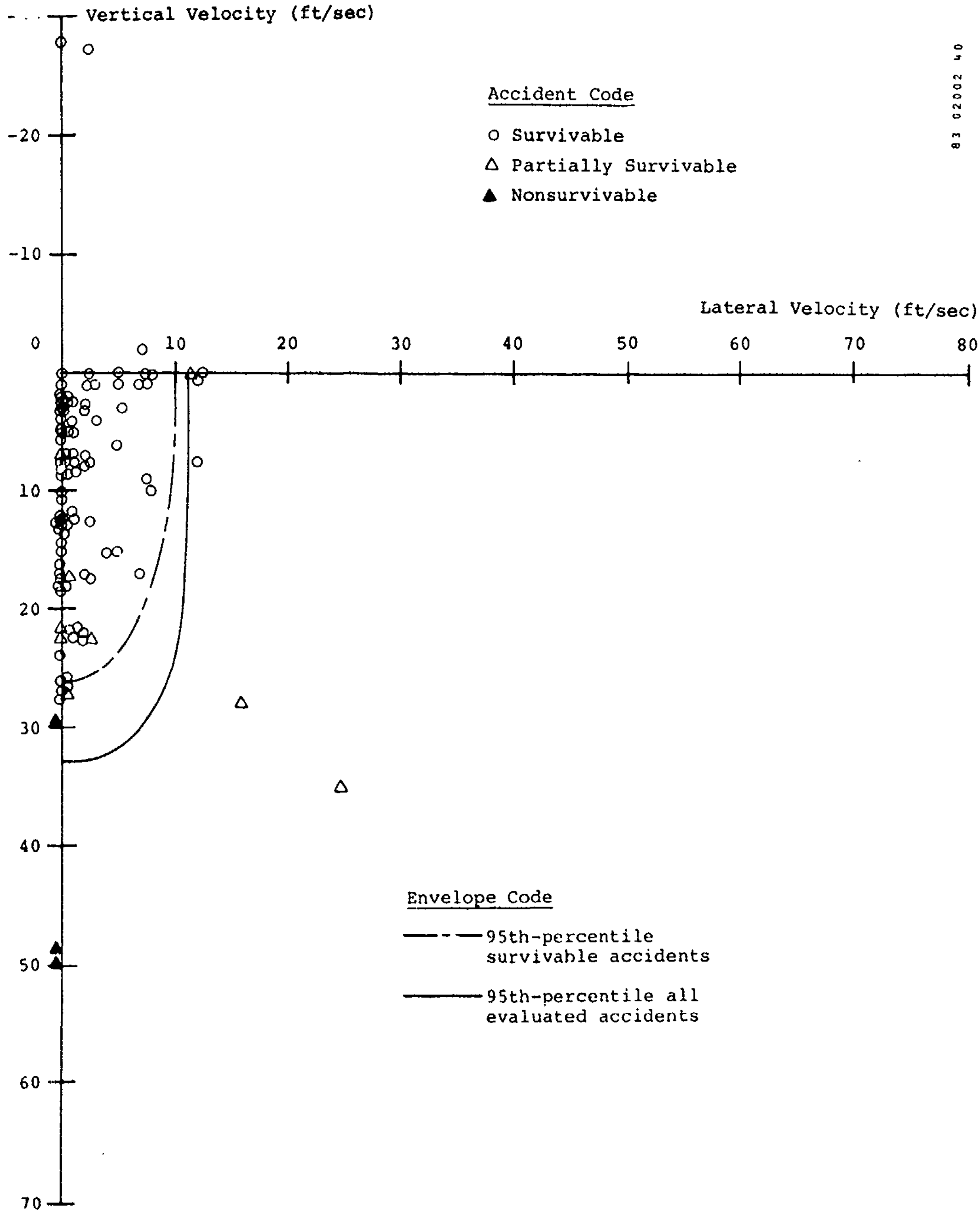


Figure 14. Accident survivability for vertical-lateral impact velocity components.

of accidents with and without postcrash fires for the longitudinal-vertical velocity components. The distribution of accidents with fire appears to be almost random; i.e., for almost any combination of impact velocities there is a significant chance of fire. The data presented in figure 17 do not indicate that there is strong correlation between the magnitude of impact velocity and occurrence of postcrash fire. However, inferring this conclusion from figure 17 is somewhat misleading. The distribution of accidents shown in this figure is a result of the inability to discern between impact damage and fire damage at higher impact speeds, which results in a lack of accidents at higher impact

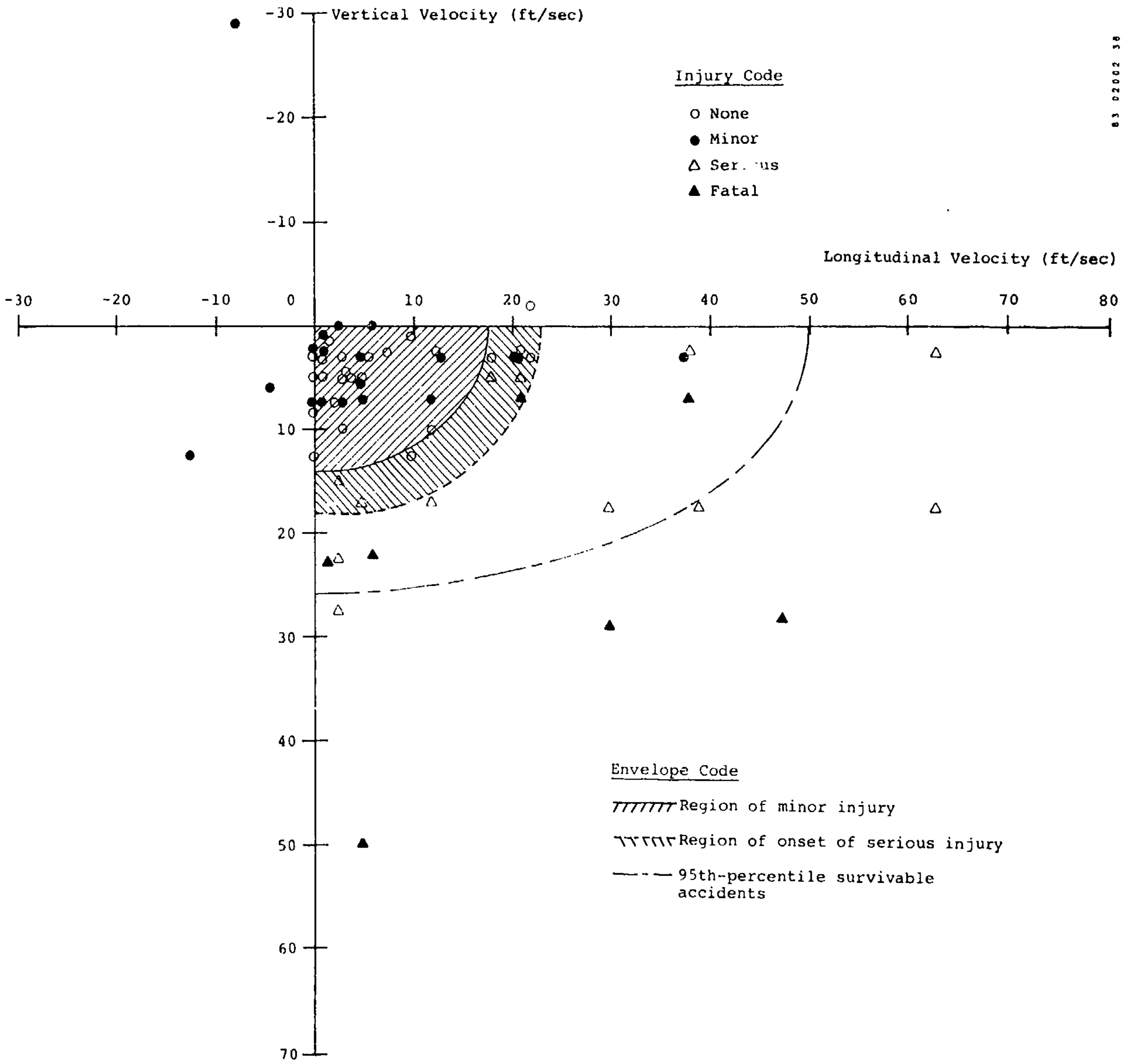


Figure 15. Injury severity distribution with lap-belt-only restraint.

velocities with known impact conditions. Therefore, only those accidents in which postcrash fire occurred and the impact velocity could be estimated by means other than damage correlation were used in figure 17.

Tabulation of the accidents with fire according to the survivability codes does indicate, as expected, that the chance of postcrash fire increases with increasing accident severity. This trend can be seen in the data presented in table 14. For the total sample of 311 accidents evaluated, 11 percent of those judged to be survivable (25 out of 226 accidents) had postcrash fires. The incidence of postcrash fire increased to approximately 43 and 52 percent for partially survivable and nonsurvivable accidents, respectively.

2.2.5 LANDING GEAR DESIGN CONSIDERATIONS. Design criteria for landing gear typically specify a minimum vertical impact velocity that can be sustained

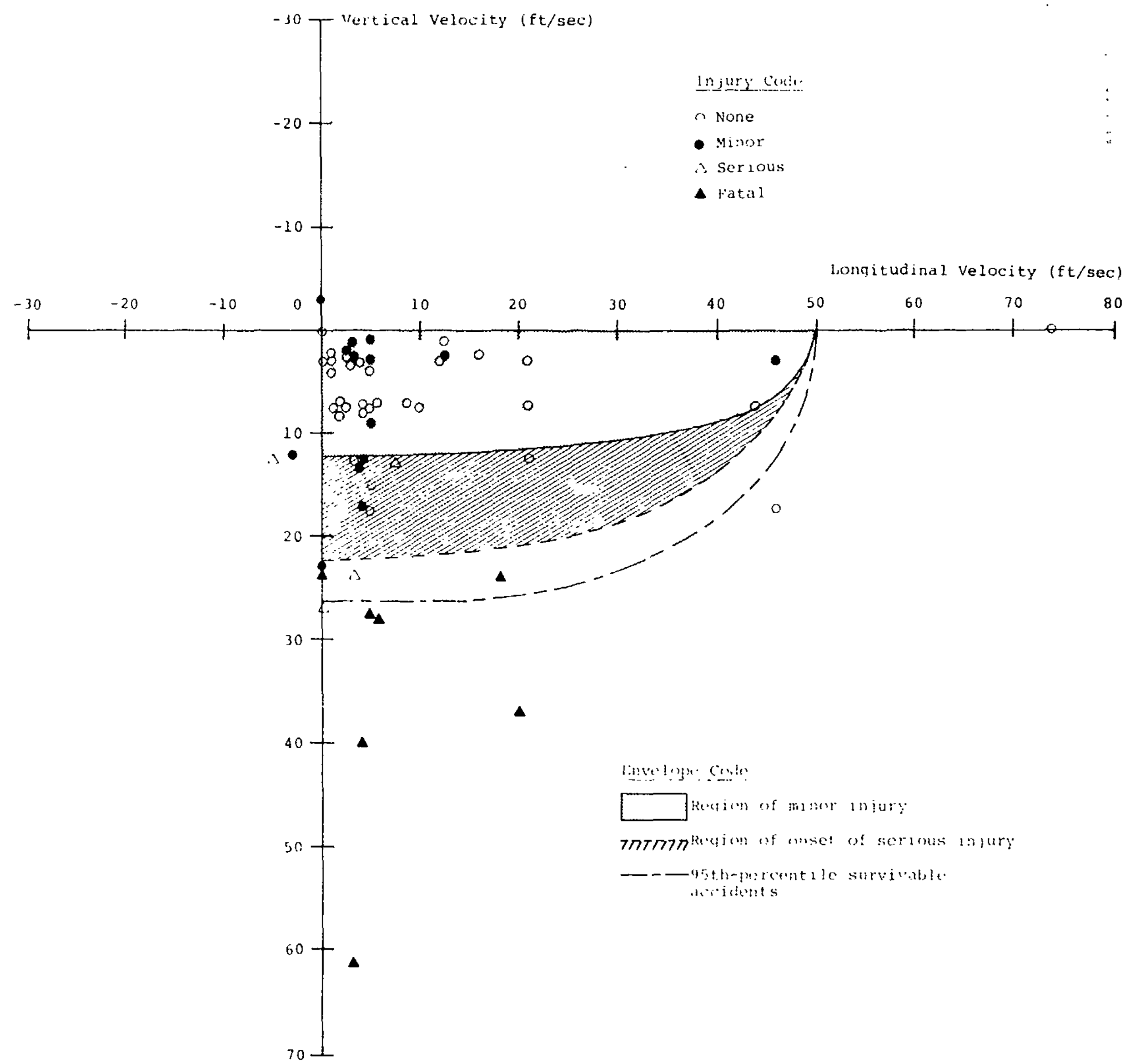


Figure 16. Injury severity distribution with lap belt and shoulder harness.

without fuselage contact, and a range of possible roll angles through which the gear must act. For a purely vertical impact, in which the gear on each side of the aircraft contacts the ground simultaneously, designs can be simple and efficient. However, the requirement to simultaneously withstand roll and vertical impact generally creates design and weight problems. These problems can be diminished, however, through an analysis of the statistical distribution of accident conditions (such as impact velocity versus roll angle), which allows an optimally balanced consideration of weight and effectiveness throughout the entire system. Minimizing the landing gear weight means that other crashworthy system components which are inherently much more weight-effective, such as upper torso restraints and energy-absorbing seats, can be utilized to provide a large percentage of the protective capability for the occupants. This approach may also apply to aircraft with retractable gear, in which the contribution of the gear to the overall crashworthiness system will be minimal.

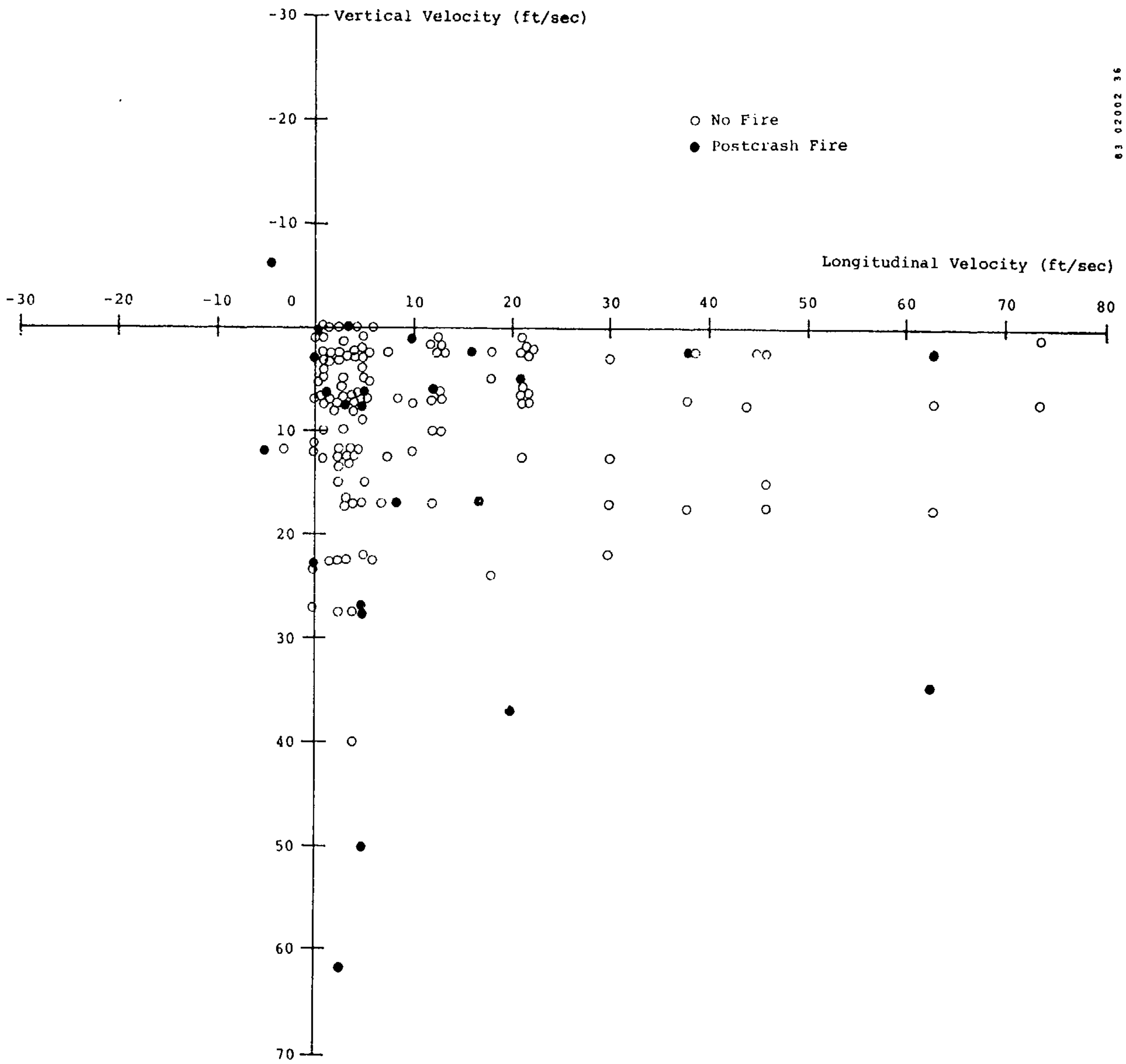


Figure 17. Distribution of accidents with postcrash fire.

It is important to develop the distribution of vertical impact velocities with roll angle in order to provide realistic design criteria. Figure 18 shows this distribution for all aircraft types.

2.3 CRASH SCENARIOS

Six crash scenarios were developed to represent the various types of impact conditions. These six scenarios include the conditions found in approximately 89 percent of all the accidents evaluated. It should be noted that these typical crash types present the findings of the actual impact conditions. Some of the scenarios are more important from an injury frequency and severity standpoint. The six crash scenarios were used to develop "design scenarios" and associated design criteria.

TABLE 14. INCIDENCE OF POSTCRASH FIRE ACCORDING TO SURVIVABILITY CODE (303 ACCIDENTS OUT OF 311 WITH KNOWN POSTCRASH FIRE HISTORY)

	Number of Accidents/Number with Postcrash Fire				
Survivability	Total Sample 1974-78	Weight Class A	Weight Class B	Weight Class C	Weight Class D
Survivable	226/25	92/15	107/8	21/0	6/2
Partially Survivable	21/9	8/4	8/3	3/1	2/1
Nonsurvivable	56/29	33/23	16/5	6/2	1/0
Total Accidents with Unknown Fire History	8	3	5	0	0
TOTAL	311	136	136	30	9

The remaining paragraphs of this section describe the six crash scenarios and their frequency of occurrence. Also, the frequency of injury for each scenario and the distribution of impact velocities is discussed.

2.3.1 SCENARIO TYPES. As discussed in the previous section, six scenarios were developed to describe typical impact conditions. The types and characteristics of the six scenarios are described on the following pages.

1. Essentially flat impact relative to ground (air to ground)

   - Landing gear can act to attenuate vertical force, although terrain features may inhibit functioning or the gear may be retracted.

   - Vertical velocity is greater than the longitudinal component (Impact angle greater than 45 degrees).

   - Angles are less than ±20-degree pitch, ±20-degree roll.

2. High longitudinal impact velocity (air to ground)

   - Longitudinal velocity is significantly greater than the vertical component (0 to 20-degree flight path angle).

   - Landing gear may be torn off and absorb very little vertical or longitudinal energy.

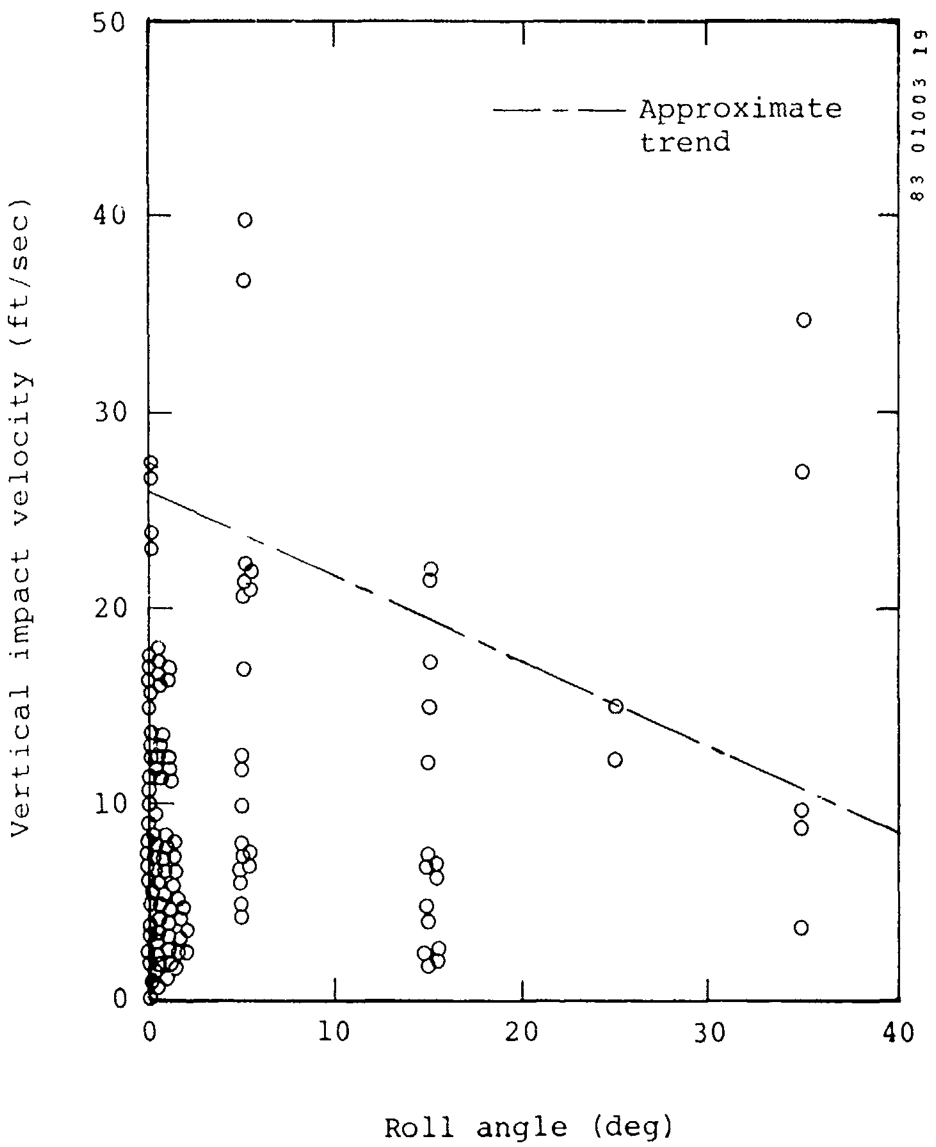


Figure 18. Impact velocity as a function of roll angle, all aircraft types, significant survivable sample (120 accidents).

- Angles are less than ±20-degree pitch, ±20-degree roll, ±20-degree yaw.

3. Rollover (ground to ground)

- Major impact is on side or top of fuselage.

- There is a low vertical or longitudinal velocity.

4. Wire impact in flight

- Aircraft has significant air speed at time of wire strike.

- The wire strike is on the frontal plane of the aircraft.
- Uncontrolled flight usually follows.

5. Water impact (air to water)

- Landing gear do not function to absorb any impact energy.
- Principal impact forces are distributed over a large fuselage area.

6. High yaw rate impact (air to ground)

- Typically component failure, or malfunction (e.g., tail rotor malfunction) leads to lateral stability control difficulties.
- Longitudinal and vertical velocity components are small, yaw rate may be large.
- Uncontrolled yawing action causes flailing-type injuries.

The evaluated accident sample contained 311 accidents. In 248 of these cases there was sufficient information to evaluate the scenario type and the impact parameters. Table 15 lists the distribution of these accidents according to the six scenario types. The most common crash scenario is the vertical impact, which accounts for approximately 28 percent of the accidents. Each of the other five scenario types accounts for approximately 10 percent of the accidents. The six scenarios represent the conditions found in 79 percent of the accident cases. The remaining accident types generally fall into two classes: the catastrophic uncontrolled flight and the relatively minor landing accidents. In this second type of accident, the impact forces may be low, but damage results primarily due to a tail-boom strike by the main rotor. Neither of these two accident types influences the crashworthiness design of the aircraft or warrants being considered as a separate scenario.

2.3.2 INJURY FREQUENCY FOR THE SCENARIO TYPES. The number and severity of injuries were tabulated for each scenario type in order to assess the relative hazard of each crash type. Tables 16 and 17 list the number of people on board the aircraft for each scenario and the percentage that received minor, serious, or fatal injuries for the total sample and for the survivable or partially survivable accidents.

Table 16, which includes the nonsurvivable accidents, shows that the vertical impact, wire strike, and water impact were the most hazardous scenarios in terms of actual number of occupants in the sample receiving fatal or serious injuries. Relatively few serious or fatal injuries occurred in the longitudinal, rollover, and high yaw rate impacts. In terms of percentage of major injury (serious or fatal), the vertical impact scenario had moderate rates (25.4 percent), although the large number of accidents for this scenario type yielded a large number of fatal and serious injuries. The wire strike and water impact accidents had very high percentages of major injuries: 65 and 63 percent, respectively. Accidents occurring in water have a high percentage of fatalities due to drownings that result from relatively minor injuries and/or problems in egressing the aircraft. The high injury rates for water are not indicative of impact

TABLE 15. ACCIDENT FREQUENCY ACCORDING TO SCENARIO TYPE

Scenario Type	Description	No. of Accidents	Percentage
1	High vertical impact velocity	70	28.2
2	High longitudinal impact velocity	21	8.5
3	Rollover	34	13.7
4	Wire strike	25	10.1
5	Water impact	24	9.7
6	High yaw rate	21	8.5
	All other	53	21.3
No. of Accidents with Known Scenario Type		248	100.0
No. of Accidents with Unknown Scenario Type		63	
TOTAL		311	

force injuries alone, but rather due to the complicating factor of postcrash survival in the water environment.

Table 17 shows the same type of comparison for the survivable and partially survivable accidents. The vertical impact and water impact scenarios again represent the most severe conditions in terms of numbers of injuries. The wire strike scenario does not appear to be as serious because a large percentage of these accidents were classified as nonsurvivable due to the uncontrollable flight characteristics following wire strike. However, studies indicate that many of these nonsurvivable accidents could actually be prevented by proper implementation of a wire strike protection system (reference 25).

2.3.3 IMPACT VELOCITIES FOR THE SCENARIO TYPES. The cumulative frequencies of vertical and longitudinal velocity were tabulated for scenarios in which these parameters would be meaningful for design purposes. Figure 19 shows the cumulative frequency curves for the vertical impact scenario using the significant survivable sample. The 95th-percentile vertical velocity for scenario number 1, 26 ft/sec, is the same as the vertical component for all significant survivable accidents in this sample. The longitudinal component for this scenario is small, with 95 percent occurring at or below 12 ft/sec.

TABLE 16. INJURY FREQUENCY FOR SCENARIO TYPES BASED ON THE TOTAL SAMPLE (248 ACCIDENTS OUT OF 311 WITH KNOWN SCENARIO TYPE)

Scenario Type	Description	Injury Percentage*			Total No. On Board	No. of Fatal and Serious Injuries*
		Fatal	Serious	Minor		
1	High vertical impact velocity	8.3	17.1	18.3	169	43
2	High longitudinal impact velocity	7.9	10.5	26.3	38	7
3	Rollover	2.4	3.7	46.3	82	5
4	Wire strike	42.9	22.4	10.2	49	32
5	Water impact	46.7	16.7	27.8	90	57
6	High yaw rate	9.5	9.5	30.9	42	8
	All other	31.9	12.9	18.9	116	52
				TOTAL	586	204

*All types of injuries included.

The longitudinal impact scenario has a large longitudinal component and a small vertical component, as expected. Figure 20 indicates that the 95th-percentile longitudinal and vertical velocity components for scenario number 2 are 72 ft/sec and 10 ft/sec, respectively.

Figure 21 shows the cumulative frequency curve for lateral velocity rollover accidents (scenario number 3). For this scenario, the principal impact forces were generally applied laterally or on the top quarter (90 to 120 degrees roll angle). The lateral velocity used to develop figure 21 was based on the impact velocity component perpendicular to the ground just prior to the principal impact. It was found that 95 percent of all rollover impacts had a lateral impact velocity of 9.2 ft/sec or less.

TABLE 17. INJURY FREQUENCY FOR SCENARIO TYPES BASED ON SURVIVABLE AND PARTIALLY SURVIVABLE ACCIDENTS (208 ACCIDENTS OUT OF 211 SURVIVABLE AND PARTIALLY SURVIVABLE ACCIDENTS WITH KNOWN SCENARIO TYPE)

Scenario Type	Description	Injury Percentage*			Total No. On Board	No. of Fatal and Serious Injuries*
		Fatal	Serious	Minor		
1	High vertical Impact velocity	0.5	17.2	19.0	163	29
2	High longitudinal impact velocity	0.	11.4	28.6	35	4
3	Rollover	2.4	3.7	46.3	82	5
4	Wire strike	9.7	35.5	16.1	31	14
5	Water impact	16.5	19.4	37.3	67	24
6	High yaw rate	0.	8.1	35.1	37	3
	Other	6.1	15.9	26.8	82	18
				TOTAL	497	97

*All types of injuries included.

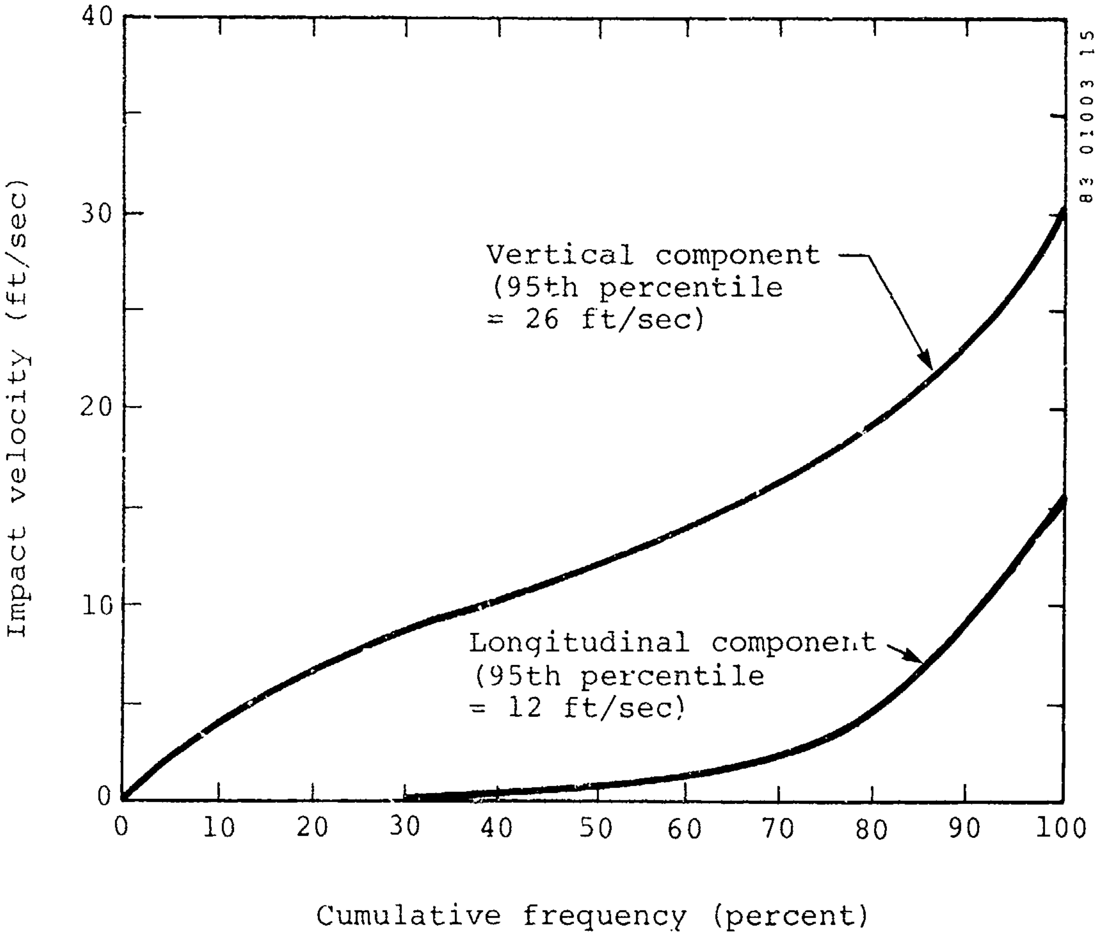


Figure 19. Cumulative frequency of occurrence of impact velocity components, significant survivable accidents, scenario no. 1 (70 accidents).

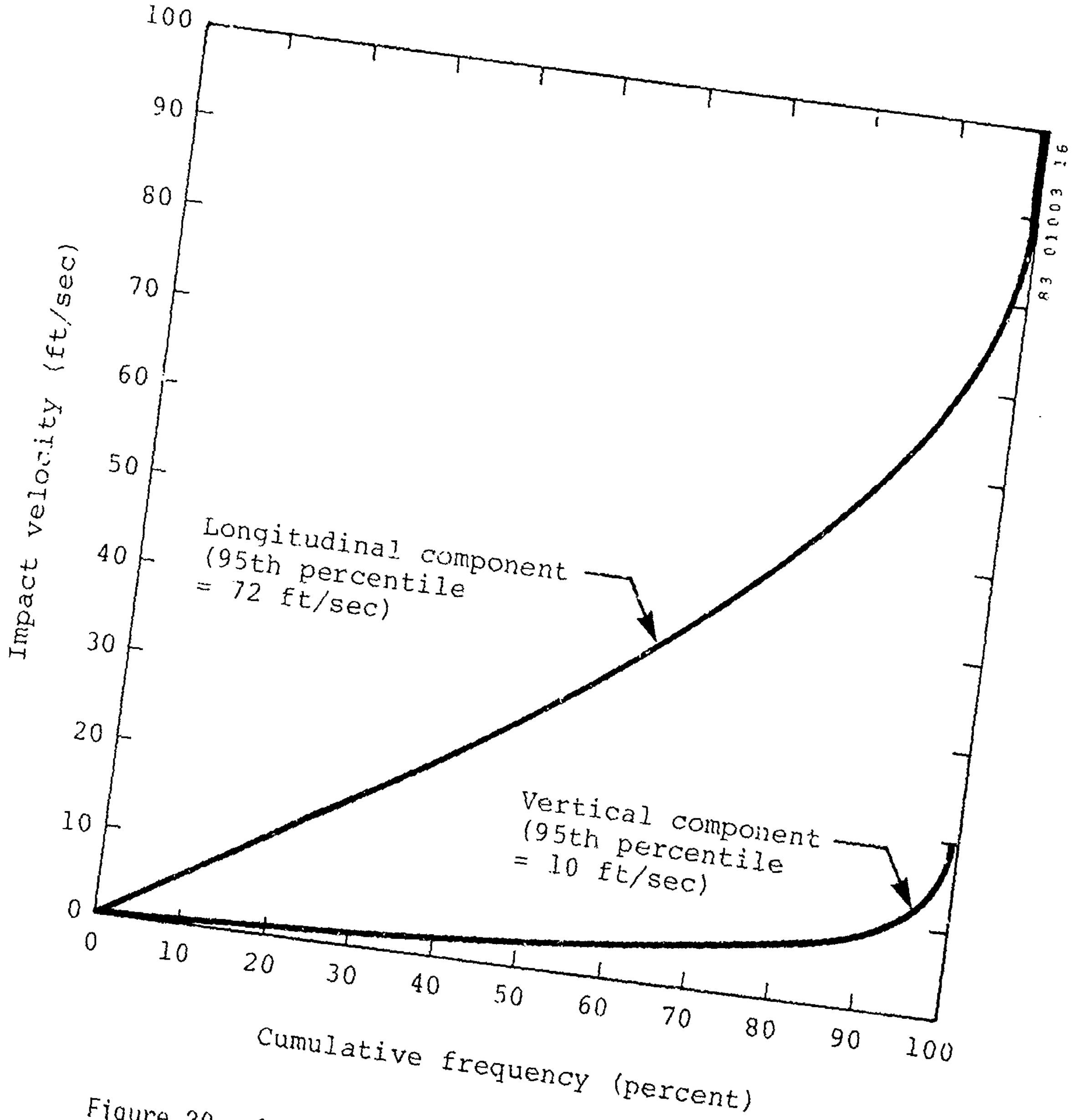


Figure 20. Cumulative frequency of occurrence of impact velocity components, significant survivable accidents, scenario no. 2 (21 accidents).

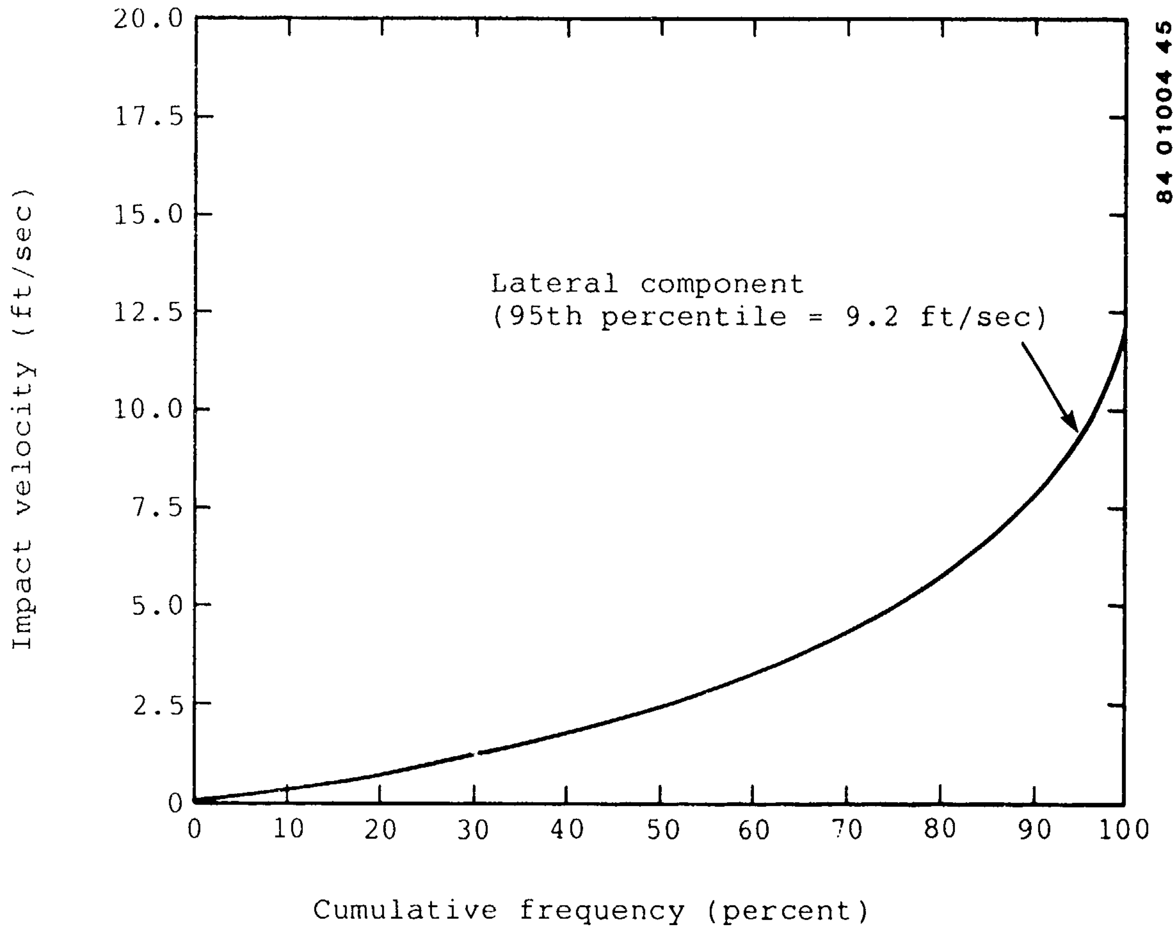


Figure 21. Cumulative frequency of occurrence of impact velocity components, significant survivable accidents, scenario no. 3 (34 accidents).

3.0 IDENTIFICATION OF INJURY/FATALITY CAUSATIVE FEATURES

The main goal of this task was to assign a cause to each known injury and to rank these causes according to the frequency and severity of the hazard. Injury descriptions were tabulated during the evaluation phase of the Task I effort described in Section 2.0. Extenuating circumstances, such as component failures or unique accident kinematics, were also noted to aid in determining the cause of an injury. The injury statistics were compiled according to severity, cause (or hazard), scenario, and aircraft weight class. The outcome of this work is a ranking of the hazards indicating the aircraft systems in need of improvement to provide occupant protection in "survivable" accidents.

As noted in Section 2.0, there are some inherent biases in the evaluated accident sample mainly due to the original investigative procedures. The final section in this chapter addresses this problem by presenting a statistical description of expected injuries and their associated causes for an average year. These statistics were based on an average of the data from the five-year evaluation period, with the known biases accounted for.

3.1 TABULATION OF INJURIES

Each injury, with an explicit description of the body region and severity, was tabulated with parameters describing the helicopter accident sequence. The primary emphasis was placed on identification of injury causes rather than a cataloging of injuries themselves. The source of this information was the Aircraft Accident Reports, obtained from the NTSB. Injury descriptions were found in the operator's or investigator's narrative, witness statements, and autopsy reports. It is generally regarded that the most reliable source of injury information is the in-patient chart or hospital discharge record (reference 26), although this was seldom available. A significant improvement in the quality of accident reporting could be attained by consistently obtaining injury information from the most reliable sources.

Injuries were categorized using the Abbreviated Injury Scale (AIS) rating system, reference 26. The separate body regions and severity codes used in the AIS are listed in tables 18 and 19, respectively. The maximum AIS rating for an injury to each of the seven body segments was used to describe the injury severity to each occupant. An overall rating of bodily injury, such as the Injury Severity Score (ISS), was not used in this study because of the need to maintain records of individual injuries for traceability of cause. The version of the Abbreviated Injury Scale used in this study, AIS-80, contains more than 500 separate injury descriptions which covered all injuries found in the accident sample with the exception of drowning. Drowning is not a trauma-related injury and therefore is not included in the AIS; however, for the purposes of this study, it was accorded an AIS rating of 6 when it was known that the drowning was a direct result of injuries sustained in the accident.

As discussed earlier in this section, a "cataloging" of specific injuries was not considered as important as the causes or hazards associated with each injury. In the remaining sections of this chapter, the AIS attributable to a particular hazard is used. The injury descriptions were taken directly from the many sources of the accident reports, and although few are written in medically acceptable terminology, most did contain, in some form, an injury description. Table 20 lists the number of accidents with injury descriptions found in the 311 accidents sample.

TABLE 18. SEPARATE BODY SECTIONS IDENTIFIED IN AIS-80 (REFERENCE 26)

Body Section	Description
External	Surface of any body region
Head	Bony skull, brain, face, eye, ear
Neck	Neck, throat
Thorax	Thoracic organs, including rib cage
Abdomen/Pelvic Contents	Abdominal/pelvic organs
Spine	Spinal column/cord
Extremities	Upper and lower limbs, bony pelvis

TABLE 19. INJURY SEVERITY CODES USED IN AIS-80 (REFERENCE 26)

AIS	Severity Code
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum injury, virtually unsurvivable
9	Unknown

3.2 RANKING OF INJURY-CAUSATIVE HAZARDS

This section describes the ranking of hazards according to the severity and frequency of injuries that they caused. The methodology used for this ranking follows the techniques developed by Hicks and Adams (reference 27) at the U.S. Army Safety Center. This technique uses a "mechanism of injury occurrence" that describes the process through which each injury occurs. The mechanism is

TABLE 20. PERCENTAGE OF ACCIDENTS WITH OCCUPANT INJURY DESCRIPTIONS ACCORDING TO ACCIDENT SEVERITY (311 ACCIDENTS IN EVALUATION SAMPLE)

Accident Severity	No. of Accidents	No. of Accidents with Documented Injuries
Survivable, no injuries	126	126*
Survivable, minor injuries	57	27
Survivable, serious or fatal injuries	75	67
Nonsurvivable	53	30
TOTAL	311	250

*The documentation contained in these accident report was sufficient to determine that no significant injuries occurred.

described in two parts: the action, or injury process, and the qualifier, or contributing factor to the injury. As an example, consider the following hazard:

ACTION: BODY EXPOSED TO FIRE

QUALIFIER: WHEN FUEL SYSTEM FAILED ON IMPACT

In this study, a set of 14 mechanisms, or hazards, were developed and each individual injury to a body region of an occupant was assigned a mechanism. Each hazard was ranked according to two factors: the frequency of injuries caused by the hazard and the most severe injuries that the hazard can cause. Tables 21 and 22 describe the ranking categories. Each hazard was then assigned to one of eight "significance groups" based on the combination of frequency and severity indicies as shown in table 23. Tables 21 through 23 were taken from reference 27.

The injury hazards within each significance group were then rank-ordered according to the accumulated AIS ratings for injuries identified in this study. The accumulated AIS is the summation of all AIS ratings for survivable accidents attributable to a particular hazard; this takes into account frequency (number of injured occupants) and injury severity. Table 24 shows the ranking of hazards ordered from most to least dangerous.

A number of provisions need to be considered in interpreting the ranking of hazards presented in table 24. The sample size of the accidents with known injuries is not directly comparable to injuries that would be expected over a certain time period. Therefore, the accumulated AIS rating is only useful for

TABLE 21. CRASH HAZARD FREQUENCY RANKING (FROM REFERENCE 27)

Frequency Index	Descriptive Nomenclature	Mathematical Definition*
A	Frequent	$0.5 < f$
B	Reasonably probable	$0.1 < f \leq 0.5$
C	Occasional	$0.05 < f \leq 0.1$
D	Remote	$0.01 < f \leq 0.05$
E	Improbable	$f < 0.01$

*f is defined as the relative frequency of occurrence of a hazard and is calculated as f = Frequency of occurrence of crash hazard/ number of accidents studied.

TABLE 22. CRASH HAZARD SEVERITY RANKING (FROM REFERENCE 27)

Severity Index	Descriptive Nomenclature	Definition*
I	Life-threatening	Results in fatal or critical injury
II	Serious	Results in major injury
III	Marginal	Results in minor injury
IV	Negligible	Results in no more than minimal injuries

*Worst credible result.

ranking the relative severity of each hazard. Paragraph 3.3 of this section considers the potential for injuries caused by each hazard for a typical year of rotorcraft accidents.

In analyzing the injury data, it was found that burn injuries occurred in approximately 20 percent of the accidents with known injuries. The injuries attributable to postcrash fires indicated that this was the most dangerous

TABLE 23. HAZARD SIGNIFICANCE GROUPS BASED ON FREQUENCY AND SEVERITY INDICES (FROM REFERENCE 27)

Significance Group	Frequency Index-Severity Index				
1	A.I				
2	A.II,	B.I			
3	A.III,	B.II,	C.I		
4	A.IV,	B.III,	C.II	D.I	
5		B.IV,	C.III,	D.II,	E.I
6			C.IV,	D.III,	E.II
7				D.IV,	E.III
8					E.IV

single hazard. Further examination of the accident reports revealed that this hazard is even more prevalent than the injuries would indicate. In an additional 25 percent of the accidents, fuel leakage occurred in close proximity to the occupants without igniting, or the occupants were extracted from the burning wreckage and/or the fire was extinguished by ground personnel before thermal injuries occurred.

The ranking in table 24 indicates that there are five hazards, all in significance group 2, that overshadow all of the other hazards that were identified in this study. The mechanisms involved in these five hazards were: burns due to fuel system failure on impact, spinal injuries due to excessive vertical loading, injuries of all types due to inflight wire strike on the frontal plane of the helicopter, secondary impact of the upper torso and head due to restraint system deficiencies, and secondary impact due to lack of upper torso restraint. Table 25 summarizes the major areas worthy of improvement, based on the injuries and fatalities which occurred in "survivable" accidents. Research and development requirements needed to provide enhanced crashworthiness are suggested. The postcrash fire hazard is ranked as the primary area for improvement due to the high number of injuries and the additional accidents in which serious fuel leaks occurred.

The accumulated AIS rating was also used to examine the relative severity of injuries for impacts in each of the six scenarios. Table 26 indicates the accumulated AIS for each scenario according to the fourteen hazards used previously in this section. The AIS ratings were based on actual injuries tabulated during the evaluation effort. The number of injuries examined represents only a small portion of the actual number of injuries occurring during the evaluation

TABLE 24. RANK-ORDERED LISTING OF CRASH HAZARDS FOR THE CIVILIAN ROTORCRAFT FLEET

Hazard Ranking	Significance Group	Description	Frequency Index	Severity Index	Accumulated AIS
1	2	Body exposed to fire when fuel system failed on impact	B	I	147
2	2	Body received excessive decelerative force when aircraft and seat allowed excessive loading	B	I	145
3	2	Body exposed to impact conditions due to inflight wire strike	B	I	110
4	2	Body struck aircraft structure because design provided inadequate clearance and/or restraint allowed excessive motion	B	I	87
5	2	Body struck aircraft structure due to lack of upper torso restraint	B	I	82
6	4	Body drowned because injuries prevented escape from aircraft	D	I	54
7	4	Body struck aircraft structure because restraint was not used properly	D	I	29
8	4	Body struck aircraft structure when structure collapsed excessively	C	II	22
9	4	Body struck aircraft structure when seat failed	D	I	12
10	4	Body struck by external object when main rotor blade entered occupiable space	D	I	12
11	4	Body struck by external object when object (other than main rotor blade) entered occupiable space	D	I	10
12	6	Body struck aircraft structure when restraint system failed	E	II	8
13	6	Body injured during postcrash egress	D	III	2
14	7	Body exposed to chemical agents on impact	E	III	1

TABLE 25. SUMMARY OF POTENTIAL AREAS FOR IMPROVED CRASHWORTHINESS IN THE U.S. CIVIL ROTORCRAFT FLEET

Priority	Potential Areas for Improvement	Resulting Hazards	R & D Requirements
1	Fuel system component failure on impact allowing fuel to come in contact with ignition sources.	1	Determine design requirements consistent with the 95th-percentile survivable impact. Develop and certify lightweight cell materials and fittings, and standardize design techniques.
2	Occupant restraint system allows longitudinal and lateral movement of upper body on impact. Cockpit and cabin geometry provides inadequate clearance.	4,5,12	Develop, certify, and require use of an effective restraint system(s) which provides longitudinal and lateral restraint for the upper body. Develop design criteria for delethalizing interior surfaces. Design goal should be to prevent injurious head and chest contact with aircraft structure in impacts up to the 95th-percentile survivable impact.
3	Airframe and seats transmit intolerable vertical loads to occupants and separate from aircraft, resulting in spinal injury.	2, 9	Conduct tradeoff studies to determine degree of protection consistent with cost, weight, and space constraints. Evaluate candidate energy absorption concepts for seats and landing gear. Develop design criteria.
4	Inflight wire strike results in uncontrolled flight and random, severe impact conditions	3	Implement wire identification and avoidance training procedures. Develop wire detection/pilot warning device. Continue certification of mechanical wire cutters.

period. Therefore, the total accumulated AIS for each scenario should be used for comparison purposes only to determine the relative severity of the hazard.

Table 26 indicates that the vertical impact scenario is the most hazardous of the six scenarios, accounting for 30 percent of the AIS total. Excessive

TABLE 26. ACCUMULATED AIS FOR CRASH HAZARDS ACCORDING TO ACCIDENT SCENARIO TYPE

Hazard No.	Description	Accumulated AIS Rating: Vertical Impact	Longitudinal Impact	Rollover	Wire Strike	Water Impact	High Yaw Rate	Total
1	Body exposed to fire when fuel system failed on impact	57	29	0	51	1	9	147
2	Body received excessive decelerative force when aircraft and seat allowed excessive loading	91	7	0	7	40	0	145
3	Body exposed to impact conditions due to inflight wire strike	0	0	0	110	0	0	110
4	Body struck aircraft structure because design provided inadequate clearance and/or restraint allowed excessive motion	22	29	17	2	13	4	87
5	Body struck aircraft structure due to lack of upper torso restraint	23	6	19	17	11	6	82
6	Body drowned because injuries prevented escape from aircraft	0	0	0	0	54	0	54
7	Body struck aircraft structure because restraint was not used properly	8	16	0	3	2	0	29
8	Body struck aircraft structure when structure collapsed excessively	2	12	0	5	3	0	22
9	Body struck aircraft structure when seat failed	8	0	0	0	4	0	12
10	Body struck by external object when main rotor blade entered occupiable space	0	0	6	6	0	0	12
11	Body struck by external object when (other object than main rotor blade) entered occupiable space	3	0	1	6	0	0	10
12	Body struck aircraft structure when restraint system failed	4	0	4	0	0	0	8
13	Body injured during postcrash egress	1	0	0	0	1	0	2
14	Body exposed to chemical agents on impact	0	1	0	0	0	0	1
	Total	219	100	47	207	129	19	721
	Percentage of Total AIS	30	14	6	29	18	3	100

vertical forces cause almost half of the injuries in accidents of this type. Wire strike is the second most hazardous scenario, accounting for 29 percent of the total AIS rating in the sample. The longitudinal and water impact conditions produce 14 and 18 percent of the total AIS score, respectively. The remaining two scenarios, rollover and high yaw rate, produce very small percentages of the injury totals, with most of these injuries of the low severity, secondary-impact type.

3.3 ACCIDENT STATISTICS FOR AN AVERAGE YEAR

Tradeoff studies for crashworthiness design require a baseline of accident and injury statistics for analysis. The statistics presented in previous sections of this chapter contain biases that skew the data toward the severe end of the spectrum. An attempt was made to account for the two known biases in the sample that were a result of the original accident investigation procedure. The first bias is in the distribution of accidents with known injuries according to the six scenarios. For example, in a significant percentage of the wire strike accidents, the injuries were known due to the large percentage of autopsies performed on the occupants. The second bias results from the investigative practice of examining accidents of greater severity or questionable cause in greater detail. Table 8 exhibits this bias by comparing the number of occupants receiving minor, serious, and fatal injuries for all accidents during 1974 to 1978 and the evaluated sample. An attempt was made to account for these biases in the development of an estimate of the number and severity of injuries occurring during a typical year in the evaluation period.

The validity of analyses based on the average year statistics requires that the following assumptions be made:

a. The fleet size and model composition did not change significantly over the five-year period.

b. The average number of flight hours per aircraft and accident rates were constant.

c. Crashworthiness of the helicopter fleet did not change dramatically over the evaluation period.

The estimate of average accident and injury statistics indicates that there were approximately 292 accidents per year involving 594 helicopter occupants. Table 27 shows the breakdown of accidents according to the weight class. The bulk of the total accidents occur in Weight Classes A and B with approximately 60 and 34 percent of the accidents, respectively. The average number of survivable and nonsurvivable accidents is listed in table 28. Approximately 8 percent of the accidents were classified as nonsurvivable and 40 percent were survivable with injuries and fatalities. The distribution of injury severity for occupants in survivable accidents and all accidents is presented in table 29. Based on the data in table 29, a total of 32 percent of the occupants in survivable accidents will be injured (175 out of 545).

Table 30 presents an estimate of the frequency and severity of injuries that were attributed to the 14 hazards identified in this program for occupants injured in survivable accidents. The rates presented in this table are averages for all models in the helicopter fleet. Note that the total injury rate for all hazards adds up to 126.8 percent. This reflects the possibility of an injured occupant receiving injuries as a result of more than one hazard.

TABLE 27. ESTIMATED AVERAGE YEARLY ACCIDENT TOTALS FOR THE FOUR WEIGHT CLASSES

Weight Class	Percentage of Accidents	Number of Accidents
A	60.0	175
B	34.2	100
C	4.1	12
D	1.7	5
	100.0	292

TABLE 28. ESTIMATED AVERAGE YEARLY DISTRIBUTION OF ACCIDENTS ACCORDING TO SURVIVABILITY AND INJURY SEVERITY

Accident Severity	Percentage of Accidents	Number of Accidents
No injuries	51.7	151
Survivable with injuries or fatalities	40.1	117
Nonsurvivable	8.2	24
TOTAL	100.0	292

TABLE 29. ESTIMATED AVERAGE YEARLY DISTRIBUTION OF OCCUPANT INJURY SEVERITY FOR SURVIVABLE AND ALL ACCIDENTS

Injury Severity	Occupants in Survivable Accidents		Occupants in all accidents	
	No.	Percent	No.	Percent
Fatal	23	4.2	67	11.3
Serious	57	10.5	62	10.4
Minor	95	17.4	95	16.0
None	370	67.9	370	62.3
TOTAL	545	100.0	594	100.0

TABLE 30. AVERAGE YEARLY INJURY FREQUENCY ATTRIBUTABLE TO THE FOURTEEN HAZARDS FOR AN OCCUPANT INJURED IN A SURVIVABLE ACCIDENT

Hazard No.	Description	Moderate Injury AIS 1 or 2 (percent)	Severe Injury AIS 3 or 4 (percent)	Life Threatening AIS 5 or 6 (percent)	Total (percent)
1	Body exposed to fire when fuel fuel system failed on impact	3.7	3.1	7.2	14.0
2	Body received excessive deceler-ative force when aircraft and seat allowed excessive loading	14.3	12.7	0.8	27.8
3	Body exposed to impact conditions due to inflight wire strike	0.7	1.5	5.9	8.1
4	Body struck aircraft structure because design provided inade-quate clearance and/or restraint allowed excessive motion	33.7	2.0	1.2	36.9
5	Body struck aircraft structure due to lack of upper torso restraint	15.3	4.6	0.8	20.7
6	Body drowned because injuries prevented escape from aircraft	0.0	0.0	3.3	3.3
7	Body struck aircraft structure because restraint was not used properly	1.2	0.7	1.2	3.1
8	Body struck aircraft structure when structure collapsed ex-cessively	5.1	0.7	0.0	5.8
9	Body struck aircraft structure when seat failed	0.7	0.8	0.4	1.9
10	Body struck by external object when main rotor blade entered occupiable space	0.0	0.0	0.7	0.7
11	Body struck by external object when object (other than main rotor blade) entered occupi-able space	0.9	0.4	0.4	1.7
12	Body struck aircraft structure when restraint system failed	0.0	0.8	0.0	0.8
13	Body injured during postcrash egress	1.2	0.0	0.0	1.2
14	Body exposed to chemical agents on impact	0.8	0.0	0.0	0.8
	TOTAL	77.6	27.3	21.9	126.8

4.0 ANALYSIS OF THE CIVIL ROTORCRAFT CRASH ENVIRONMENT

4.1 INTRODUCTION

Current regulatory standards for helicopter design address minimum requirements for crashworthiness. At the time of their inception, little information on crash survival was available, and since that time most of the crashworthiness advances in civilian helicopters have been attained through "voluntary" efforts of the manufacturers. However, in the foreseeable future, it is expected that crashworthiness design requirements will be introduced for civilian rotorcraft.

The FAA has initiated programs such as this one to provide necessary information for the decision-making process. Such information should enable the FAA to determine if modifications to the Federal Aviation Regulations (FAR) are warranted. This section discusses some of the considerations involved in setting a level of crashworthiness to be attained in civilian rotorcraft. The remaining paragraphs of this section compare the civil helicopter crash environment to human tolerance, to the military crash environment, and to the capabilities of crashworthy systems in existing production aircraft.

4.2 COMPARISON OF HUMAN TOLERANCE TO THE CIVIL ROTORCRAFT CRASH ENVIRONMENT

Generally three classes of injuries are considered when discussing human tolerance in a crash environment: internal injuries due to whole-body deceleration, secondary impact injuries due to contact with surrounding structure, and fire-related injuries due to thermal exposure or inhalation of combustion products. The first two classes of injuries are directly related to the principal impact forces, and they are dealt with in the following paragraphs. Thermal injury is generally a postcrash survival problem and it is treated separately in paragraph 4.3.4.

A substantial amount of information has been compiled on tolerance to whole-body acceleration. Studies have been conducted with human volunteers approaching the onset of significant injury, and beyond this point with animal surrogates. Unfortunately, the acceleration levels that cause specific injuries are not easily defined due to the wide variation in strength of human tissues. Eiband's compilation of human tolerance (reference 10) to whole-body acceleration is generally used as a guideline for setting injury-producing levels, and will be used here. The remainder of this section compares the velocity components, found in Task I of this study, to the ability of the body to withstand the associated forces.

Secondary impact can range from comparatively minor extremity injury, to life-threatening chest and head damage. Delethalization of interior surfaces could lessen the severity of injury due to secondary impact; however, this is not an effective preventive measure. Restraint of the body to preclude impact of the chest and head is the most effective means of reducing the secondary impact hazard. For a well-restrained occupant in a crash environment, whole-body acceleration becomes a limiting factor in the body's ability to withstand the restraining forces.

4.2.1 WHOLE-BODY ACCELERATION TOLERANCE TO 95TH-PERCENTILE CRASH LEVELS. The 95th-percentile significant survivable velocity components were identified in

Task I of this effort (Section 2.0). However, human tolerance data are generally expressed in terms of acceleration, which is a design-dependent function related to the crushing characteristics of the airframe. A range of acceleration pulse shapes were examined for each of the 95th-percentile velocities to determine if the resultant acceleration environment would be hazardous by known standards. Table 31 shows five possible deceleration pulses for each velocity component. These were derived based on characteristic stopping distances in the vertical and lateral directions (6 in.), and in the longitudinal direction (2 to 10 ft).* The vertical and lateral stopping distances represent the ground deformation and crushing of the aircraft structure in the principal impact. Landing gear deformation was not considered since the forces are generally low and contribute little to slowing the aircraft in a crash of maximum severity. The longitudinal stopping distance is often several orders of magnitude longer and represents the distance that the aircraft moves parallel to the ground while being slowed by contact forces. If the contact forces are low, such as friction between the ground and aircraft fuselage, then the stopping distance will be large, often exceeding 100 ft. However, longitudinal stopping distances can be very short, on the order of 2 ft, if the underfloor structure begins to plow and scoop the ground or water. Equations for calculation of the acceleration pulse characteristics are presented in Appendix C.

Two assumptions were made in using this analysis to relate the crash environment to human tolerance. First, it was assumed that the occupant was subjected to the same deceleration pulse as that derived for the airframe in table 31; i.e., there was no dynamic overshoot in the interface between the occupant and airframe. This factor needs to be considered in interpreting this simple analysis, since in the vertical direction, there is almost always an amplification of the input pulse due to the elastic structure of cushions and buttock tissue. There can also be a dynamic overshoot in the longitudinal or lateral direction if the restraint system uses high elongation webbing or if restraint system slack exists at the time of the accident. The second assumption was that the effects of combined-mode impact need not be considered, i.e., that the aircraft velocity vector at impact was parallel to the direction used in development of the human tolerance data.

Figure 22 presents a comparison of the human tolerance criteria for headward ($+G_z$) acceleration within the environment produced by the five pulse shapes shown in the first column of table 31. Even without considering the effects of dynamic overshoot, the five pulse shapes all fall in the region of moderate injury. Figure 23 shows the relative frequency of spinal injuries, based on the data collected in Task II, for various vertical impact velocities. The curve in figure 23 indicates a 50-percent spinal injury rate for a 26-ft/sec vertical impact.

Human tolerance to spineward ($-G_x$) acceleration with adequate restraint is very high, with incidents of voluntary exposures exceeding 40 G causing no permanent damage. The relationship between these human tolerance data and the projected crash environment is shown in figure 24. For both stopping distances examined (2 ft and 10 ft), the curves fall within the ranges of uninjured, voluntary

*These stopping distances were chosen as representative of the survivable accidents investigated.

TABLE 31. POSSIBLE DECELERATION PULSE SHAPE CHARACTERISTICS FOR THE 95TH-PERCENTILE SURVIVABLE VELOCITY CHANGES

	Vertical impact	Lateral impact	Longitudinal impact	
Initial velocity Final velocity Stopping distance	26 ft/sec 0 6 in.	10 ft/sec 0 6 in.	50 ft/sec* 0 10 ft	50 ft/sec 0 2 ft
	Deceleration pulse characteristics			
Rectangular	21 G .038 sec	3 G .100 sec	4 G .400 sec	19 G .080 sec
Triangular	28 G .058 sec	4 G .150 sec	5 G .600 sec	26 G .120 sec
Triangular	42 G .038 sec	6 G .100 sec	8 G .400 sec	39 G .080 sec
Triangular	56 G .028 sec	8 G .075 sec	10 G .300 sec	52 G .060 sec
Half sine	33 G .038 sec	5 G .100 sec	6 G .400 sec	30 G .080 sec

*Note time scale change for this column.

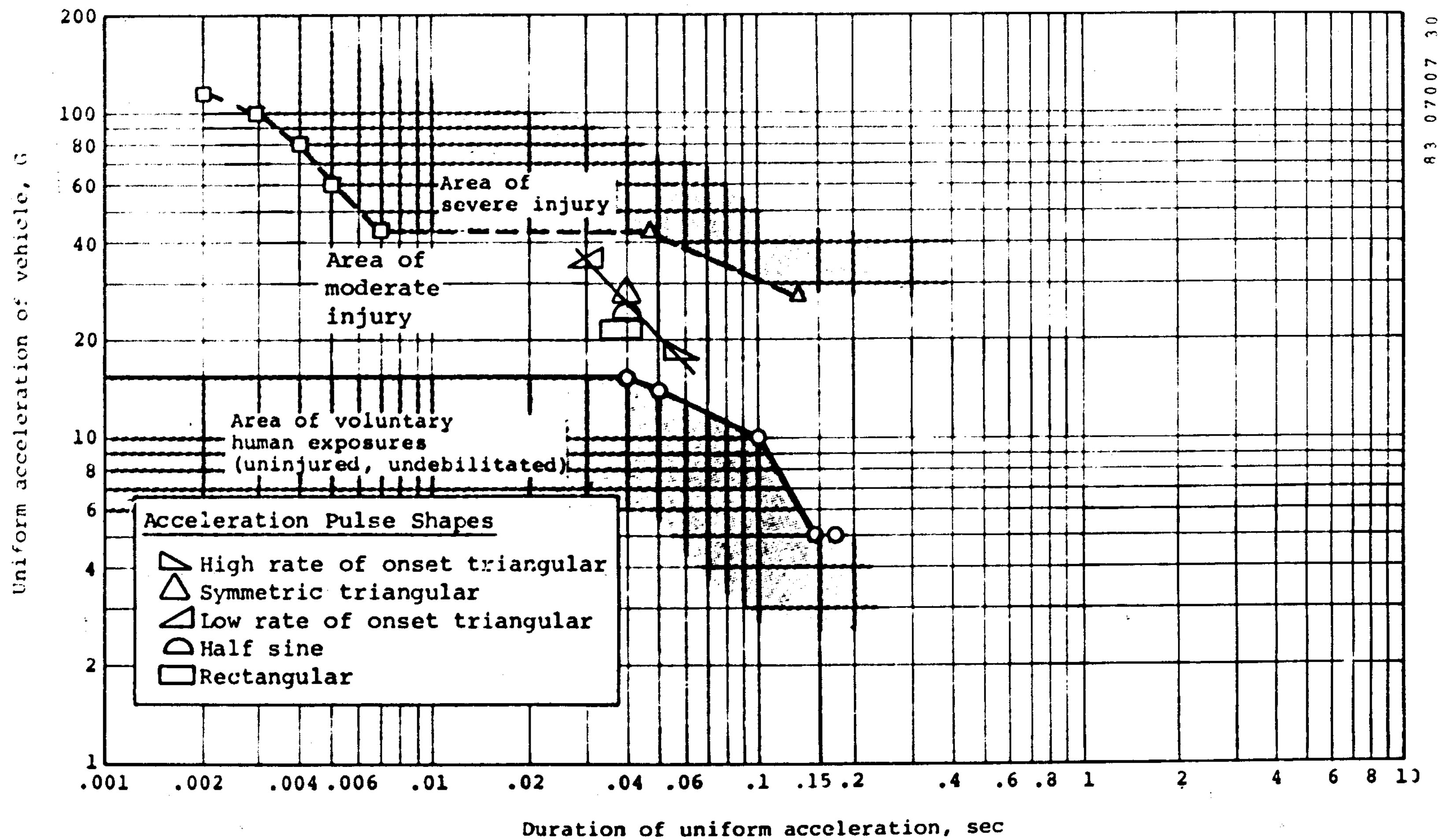


Figure 22. Duration and magnitude of headward acceleration endured for various vertical deceleration pulses described in table 31.

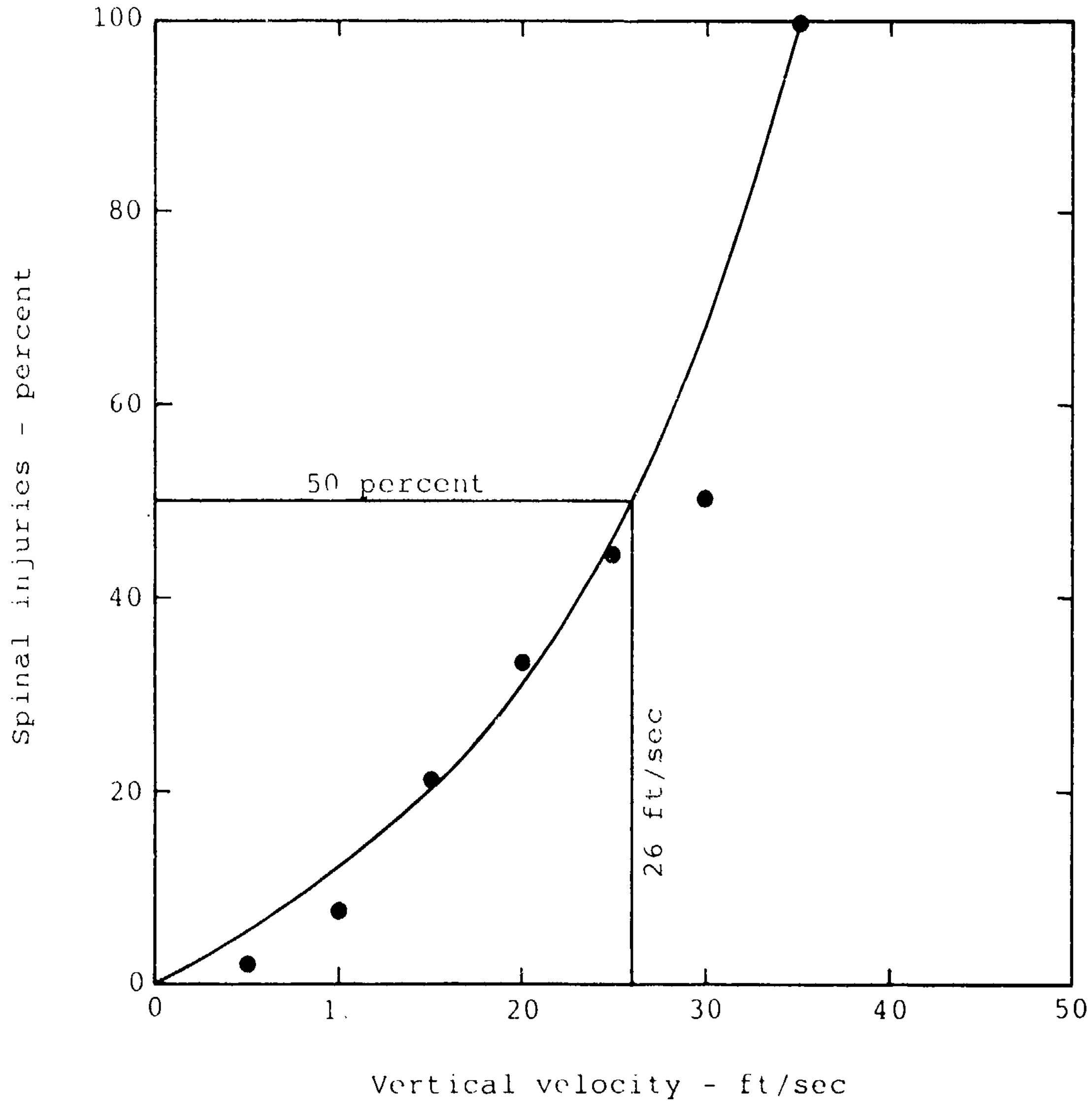


Figure 23. Relative frequency of spinal injuries versus change in vertical velocity for occupants in U.S. Civil rotorcraft accidents.

exposure, as is confirmed by the data collected in this study. In all the accidents included in the sample the incidence of injury for well-restrained occupants in high-speed longitudinal crashes was almost zero, as shown in figure 16.

There has been very little research conducted on whole-body tolerance to lateral (G_y) acceleration. However, in one test with a volunteer an average acceleration of 11.5 G was endured for 0.1 sec. This impact greatly exceeds the environment that the 95th-percentile lateral velocity component of 10 ft/sec would produce. The statistics tabulated in this study for rollover-type crashes, which represented the bulk of the lateral impacts, indicated that most injuries were of the low-severity, flailing type, rather than the internal injury type often caused by excessive acceleration.

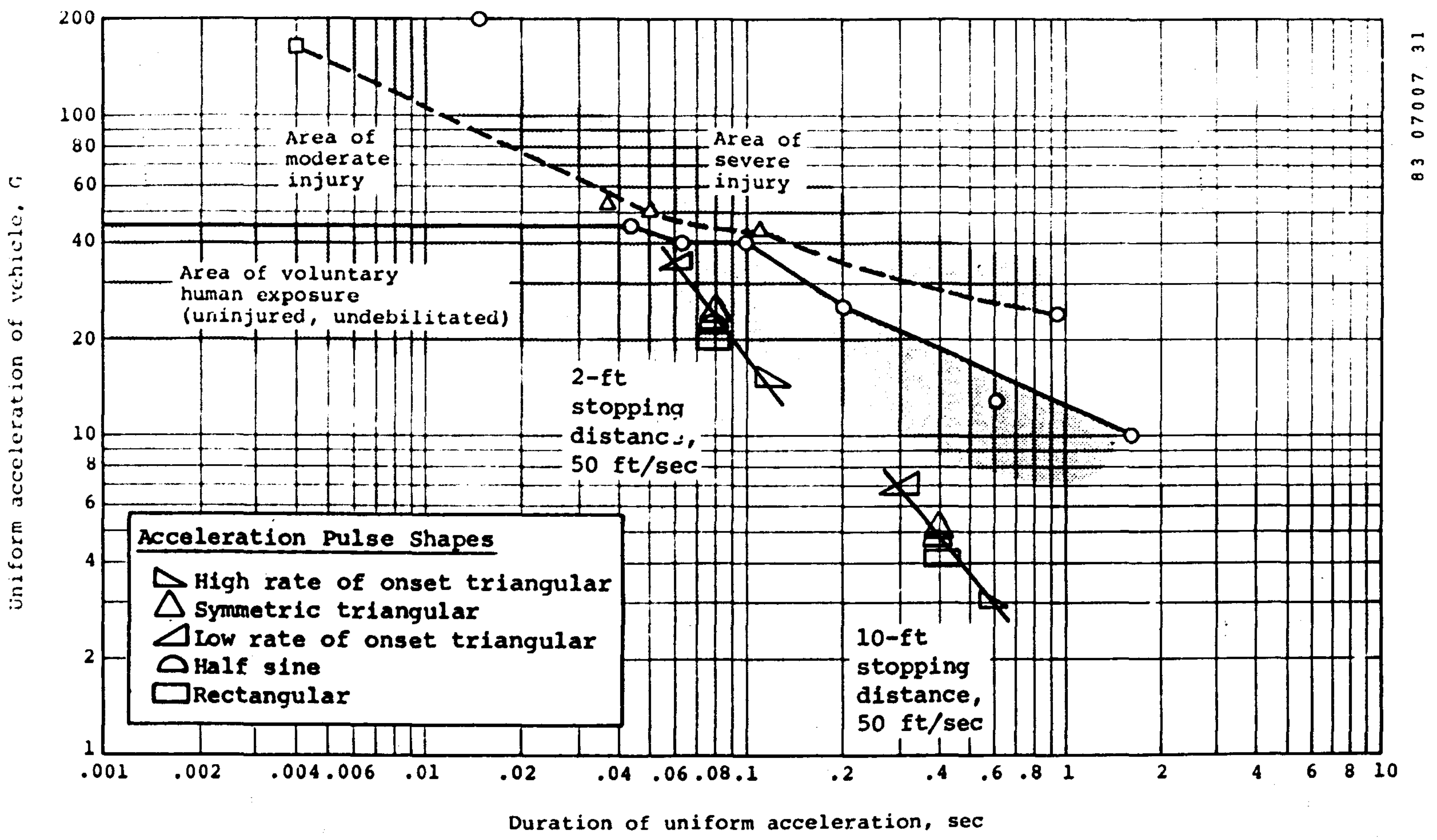


Figure 24. Duration and magnitude of spineward acceleration endured for various longitudinal deceleration pulses described in table 31.

4.2.2 CONCLUSIONS BASED ON HUMAN TOLERANCE. This simple analysis of the crash environment for the 95th-percentile velocity components indicates that only in the vertical direction do the conditions approach the human tolerance level. This is validated by the large number of spinal injuries that were found. Therefore, in the vertical direction there is a need to modify the acceleration environment experienced by an occupant through the use of load-limiting landing gear, fuselage structure, or seats (or possibly a combination of these items). It should be noted that load-limiting devices may also be desirable, although not required by human tolerance, in the longitudinal or lateral directions to reduce peak structural loads under crash conditions. Also, although no proof has been presented here, it is generally acknowledged that human tolerance to fires and secondary impact to the head and chest is low enough to require preventive measures, such as fuel containment and adequate restraint in crashworthy aircraft.

4.3 COMPARISON OF THE CIVIL AND MILITARY ROTORCRAFT CRASH ENVIRONMENT

A comparison of the civil and military crash environments was conducted to determine the relative degrees of similarity between the typical impact conditions. The intent was to determine which aspects of military crashworthiness technology and existing hardware are applicable to the civil helicopter fleet. Data used for this comparison were compiled from the sources listed in table 32.

4.3.1 TERRAIN AT IMPACT SITE. A comparison of the primary terrain features at the impact site for civil, U.S. Army, and U.S. Navy aircraft is shown in figure 25. Civil accident experience differs significantly from the military only in the larger number of accidents that occurred on prepared surfaces or into water. Accidents in which landing gear would have had the opportunity to function included those accidents on soft ground, prepared surface, and frozen ground (see table 7 for description of terrain). Sixty-two percent of the civil accidents studied were in this category, which is similar to the 58 percent indicated in the Army aircraft study. Thus, the percentages of civil and military accidents in which the gear could have functioned were approximately the same. On this basis it would be desirable to use the landing gear in the energy absorption system (gear, fuselage, and seats) of civil helicopters to the same degree as is currently used in U.S. Army helicopters, i.e., for about 20 percent of the energy absorption capability.

4.3.2 AIRCRAFT ATTITUDE AT IMPACT. The helicopter attitude at impact is described in terms of the pitch, roll, and yaw angles. Figures 26, 27, and 28 show that the distribution of these angles is approximately the same for the civilian and Army accident samples. Thus, it would appear that civilian crashworthiness design requirements could follow (in form) those used by the U.S. military with appropriate modifications made to account for differences in impact velocities for the civil crash environment.

4.3.3 SURVIVABLE IMPACT VELOCITIES. A comparison of the civilian and military impact velocity components indicates that, as a group, the civilian accidents occur at lower velocities. Figure 29 shows the 95th-percentile survivable vertical-longitudinal velocity component curves for civilian, Army, and Navy helicopters. It can be inferred from this comparison that 95 percent of all civilian helicopter crashes occur at significantly lower vertical impact speeds than do those of the Army or Navy fleets (with the exception of the data compiled for the Army OH-58A). Based on current design trends, vertical impact speed has the greatest influence on crashworthy design. Therefore, the human body can tolerate

TABLE 32. SURVEY OF REFERENCES USED IN COMPARISON OF THE CIVIL AND MILITARY CRASH ENVIRONMENT

Aircraft	Source	Reference No.	Accident Period	Accident Selection Criteria
Civil Helicopter Fleet	Chapter 2 and 3 of this Report	-	1974 - 1978	Significant survivable conditions: a. Postcrash fire, or b. At least one injury, or c. Substantial structural damage
U.S. Army Rotary-Wing and Light Fixed-Wing Aircraft	Aircraft Crash Survival Design Guide USARTL-TR-79-22B	(2)	July 1960 - June 1965 Jan. 1971 - Dec. 1976	One or more of following conditions: a. Substantial structural damage b. Postcrash fire c. Personnel injuries d. At least one survivor
U.S. Army OH-58A	Engineering Analysis of Crash Injury in Army OH-58A Aircraft USASC-TR-79-1	(28)	1971 - 1976	All OH-58A accidents
U.S. Army Helicopter Fleet	Analysis of U.S. Army Aviation Mishap Patterns USAARL-TR-82-2	(29)	1970-1981	Unknown
U.S. Army Helicopter Fleet (Bell Helicopter Study)	Helicopter Landing Gear Design and Test Criteria Investigation USAAVRADCOM-TR-81-D-15	(24)	1974 - 1978	All Accidents of Army Helicopters
U.S. Army Helicopter Fleet	Helicopter Crashworthy Fuel Systems and Their Effectiveness in Preventing Thermal Injury	(30)	1968 - 1976	All Accidents of Army helicopters
U.S. Navy Helicopter Fleet	A Study of Naval Aircraft Crash Environments with Emphasis on Structural Response	(31)	Jan. 1969 - May 1971	Survivable Accidents with: a. Aircraft destruction or substantial damage b. Takeoff, landing, or inflight phase of operation c. Occupants involved in crash

very little vertical loading; the impact energy must be absorbed within the aircraft structure through controlled crushing. Since the absorbed impact energy is proportional to the square of the impact velocity, the differences exhibited between the civilian and military vertical crash environment have significance.*

*The impact energy is approximately equal to the difference in kinetic energy before and after the principal impact. In equation form:

$$\text{Impact energy} = \frac{1}{2} m \left(V_i^2 - V_f^2\right)$$

where m = mass of the aircraft
V_i = initial vertical velocity
V_f = final vertical velocity

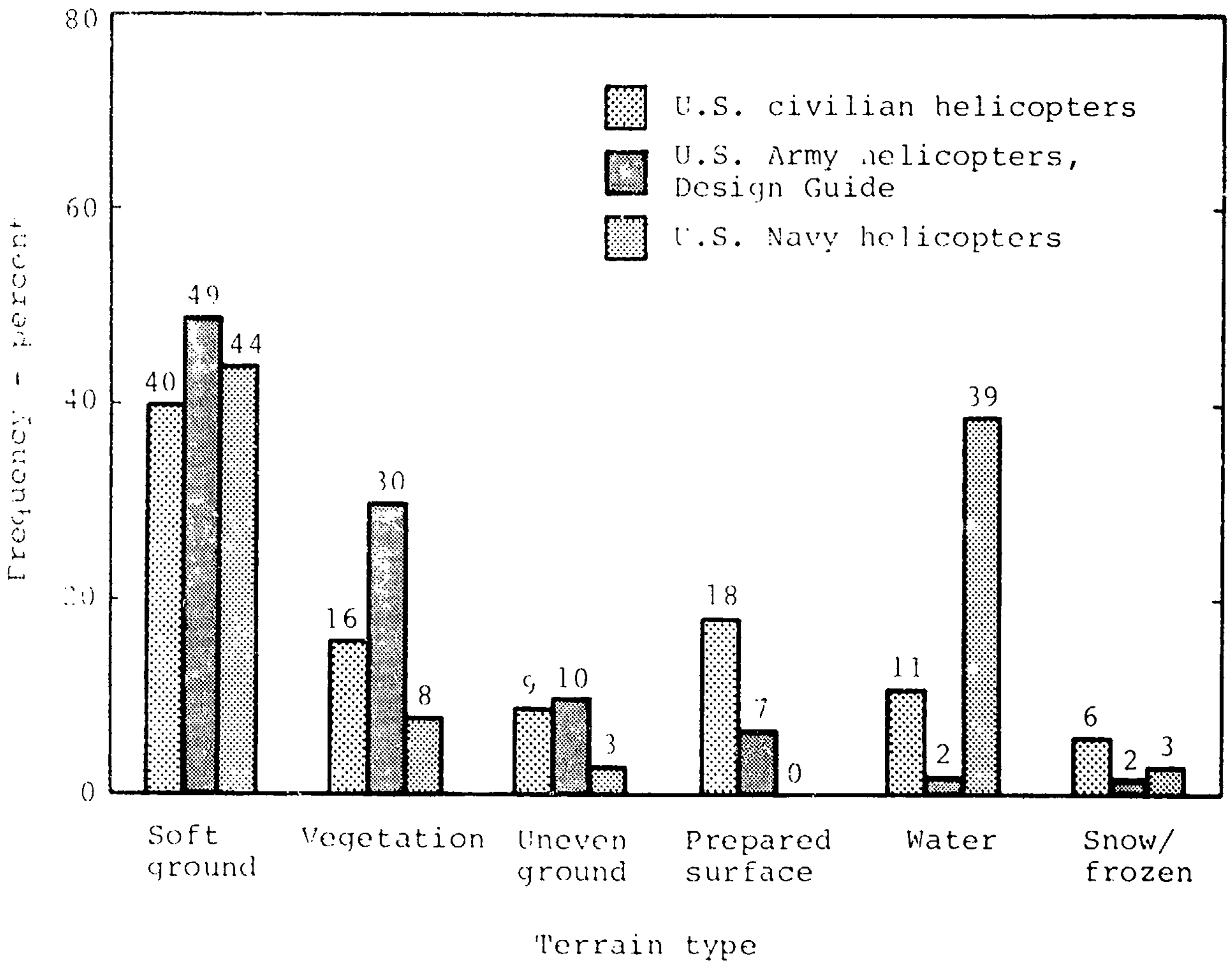


Figure 25. Comparison of primary terrain features at impact site for civil and military helicopter accidents.

For example, there is a factor of 2.6 between the amount of vertical energy that must be absorbed in the U.S. Army design requirement of 42 ft/sec and in the 95th-percentile survivable level of civilian accidents, 26 ft/sec. The military vertical energy absorption requirement is clearly not necessary for civilian aircraft and would impose a significant, and unjustifiable, weight and cost penalty.

In the longitudinal direction, the civil and Army accidents show reasonably similar velocities, converging at approximately 50 ft/sec and indicating that typical flight characteristics seldom produce crashes exceeding this level. The 95th-percentile velocity curve for the U.S. Army OH-58A is shown in figure 29 to illustrate an important point: under the right conditions, with proper restraint and an underfloor structure that resists "plowing," very high longitudinal velocities can be sustained. The U.S. Army Safety Center has determined that the longitudinal 95th-percentile survivable level in the OH-58A is approximately 140 ft/sec (reference 28). Although these high velocities are survivable, it would be hard to justify setting design requirements to these levels when 95 percent of all the survivable civilian accidents occur below 50 ft/sec. It

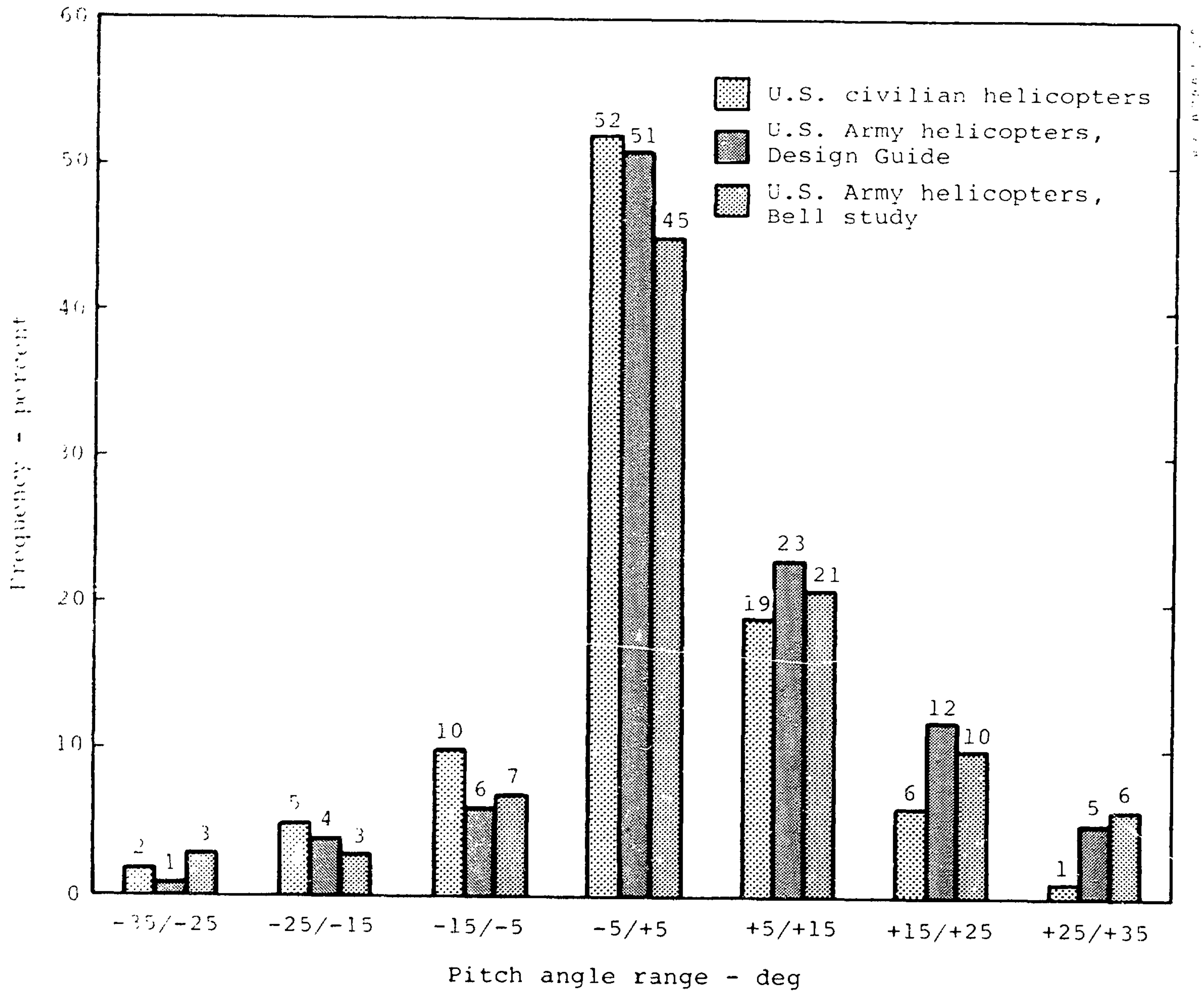


Figure 26. Comparison of aircraft pitch angle distribution for civil and Army helicopter accidents.

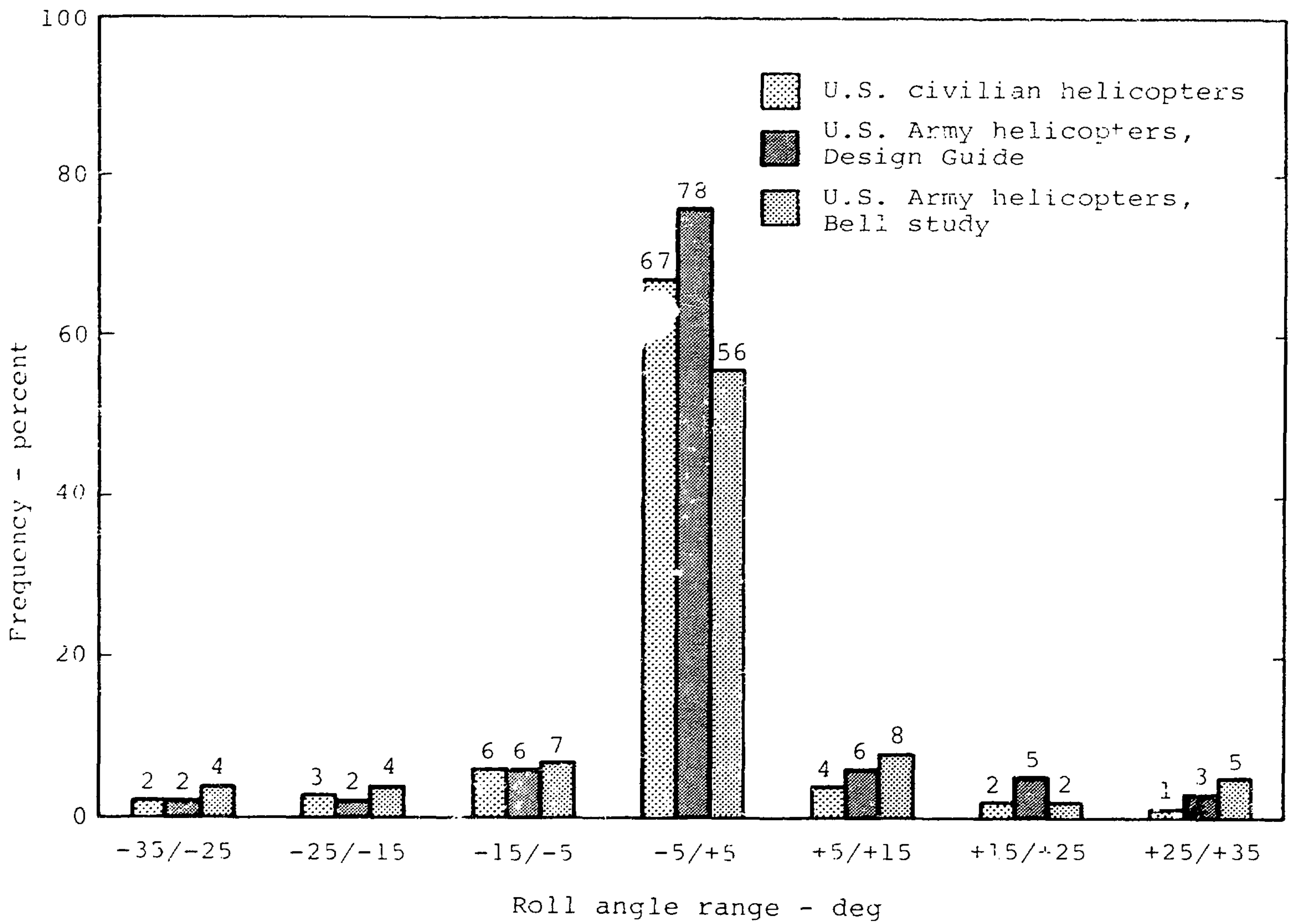


Figure 27. Comparison of aircraft roll angle distribution for civil and Army helicopter accidents.

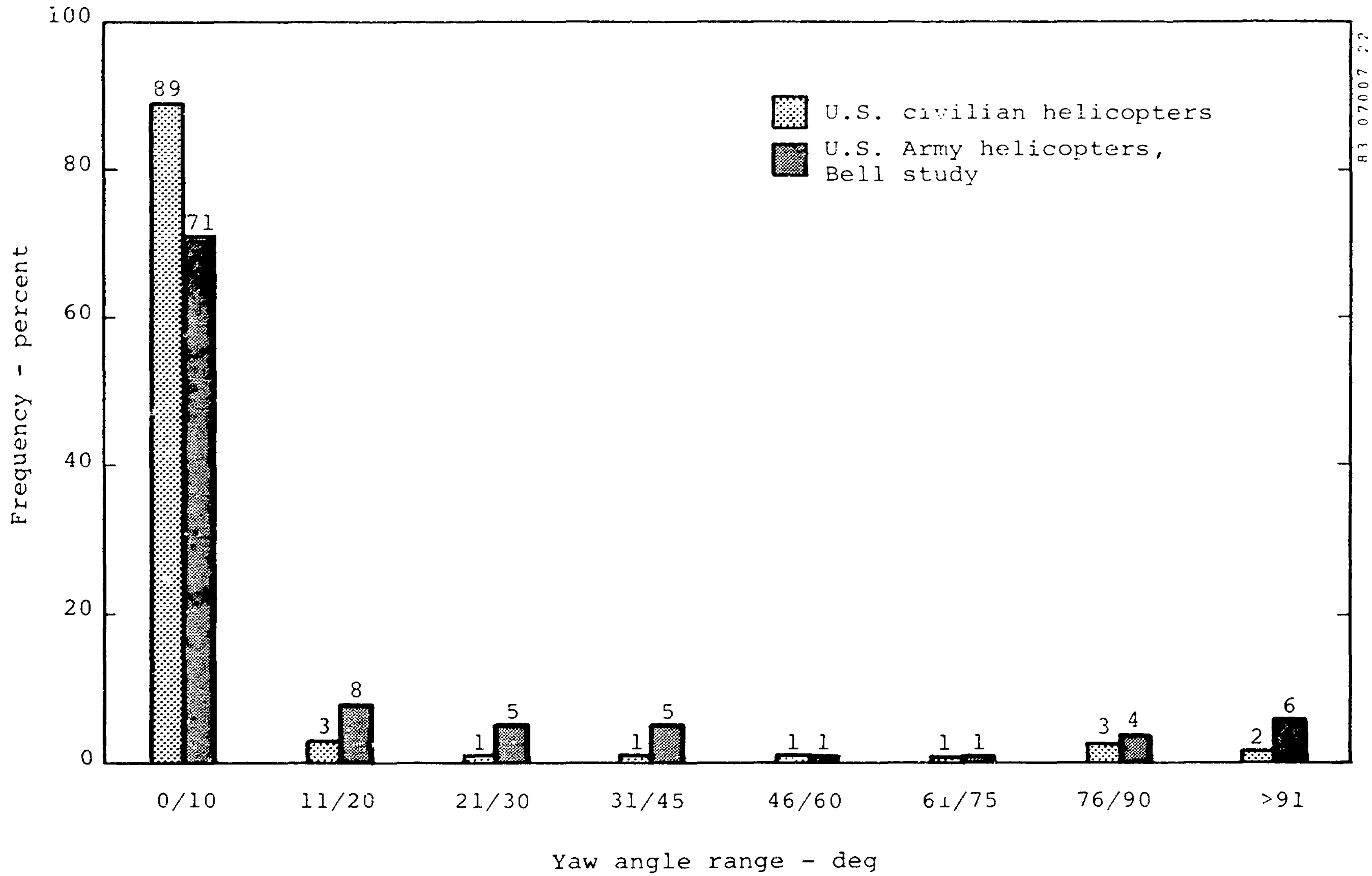


Figure 28. Comparison of aircraft yaw angle distribution for civil and Army helicopter accidents.

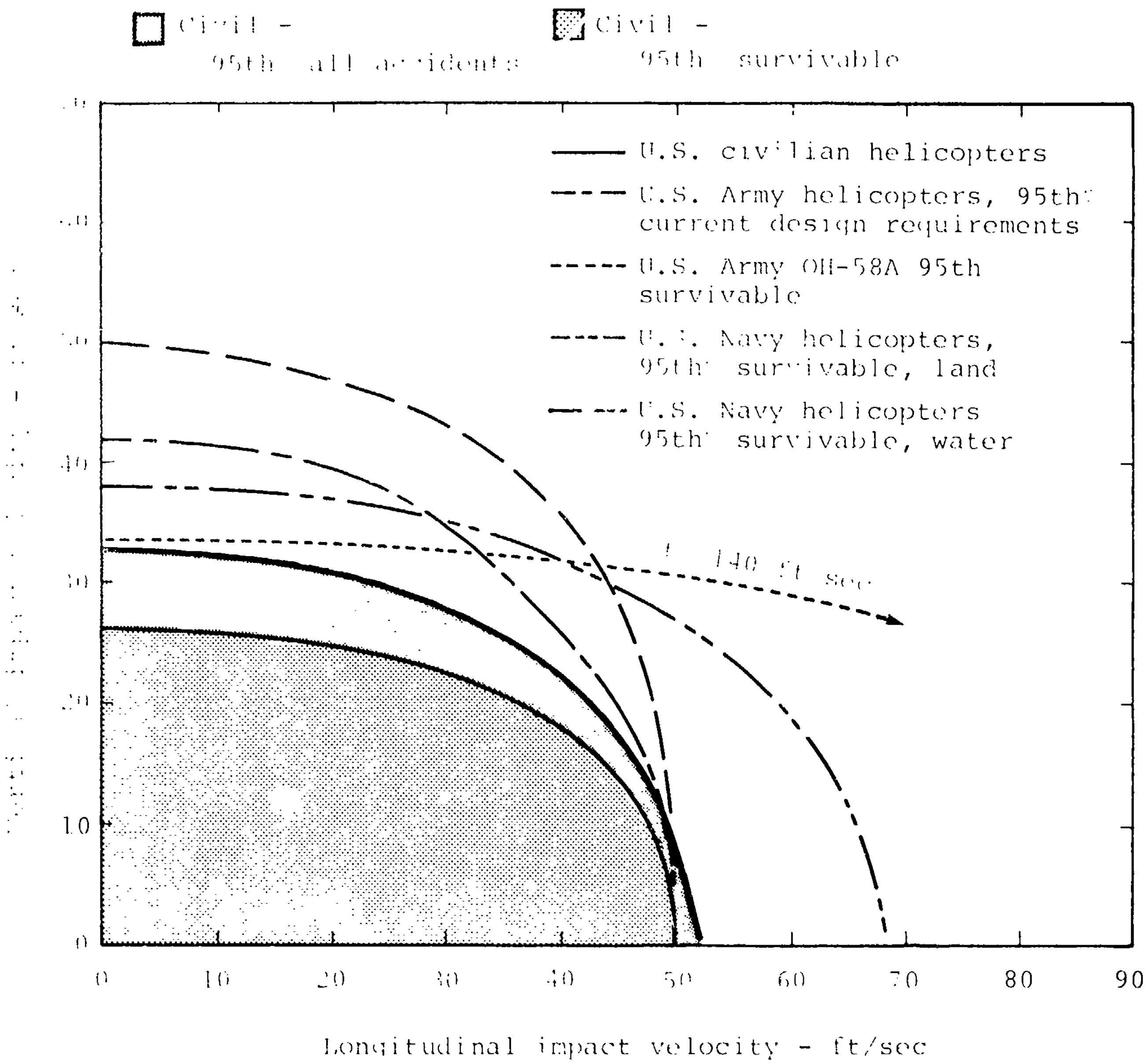


Figure 29. Comparison of the civilian and military 95th-percentile impact velocity components.

should also be noted that the demands placed on an aircraft to resist longitudinal impacts are relatively low, as evidenced by the fact that the OH-58A model, which was not designed to rigorous crashworthy requirements, provides remarkably good protection for longitudinal impacts.

There are two important conclusions that can be drawn from this comparison of the civilian and military impact velocity profiles:

1. The vertical military design requirements are more severe than required for civilian helicopters, considering the distribution of accidents for the two groups.

2. In the longitudinal direction, the military and civilian accidents show reasonably similar impact velocities, indicating that the military design methodology for occupant retention and resistance to plowing of the fuselage should be directly applicable.

4.3.4 POSTCRASH FIRE HAZARD. The data compiled on the hazards of postcrash fire in U.S. Army helicopter accidents are detailed and conclusive (reference 30). In 1,000 non-combat, survivable accidents for helicopters without the U.S. Army Crashworthy Fuel System (CWFS), there were 133 postcrash fires, 13.3 percent of the accidents. In the civilian study it was found that 34 out of 247 accidents involved postcrash fires, or 13.8 percent. Therefore, the military and civilian postcrash fire hazard appears to be very similar. Table 33 compares the injury experience of non-CWFS equipped civilian and military helicopters involved in survivable accidents. Approximately 11 percent of the injuries and fatalities in Army helicopters were caused by fires. In comparison, 14 percent of the injuries and fatalities in civilian accidents were thermally induced. These statistics point out the very severe hazard associated with postcrash fires.

TABLE 33. INJURIES AND FATALITIES IN SURVIVABLE ACCIDENTS FOR HELICOPTERS NOT EQUIPPED WITH CRASHWORTHY FUEL SYSTEMS

	Injuries		Fatalities		Percentage of Injuries and Fatalities
Sample	Thermal	Non-Thermal	Thermal	Non-Thermal	Caused by Fire
U.S. Army Helicopters 1967-1969 1000 Accidents 133 Postcrash Fires	64	1,297	95	159	10.9
U.S. Civilian Helicopters 1974-1978 86 Accidents with known injuries	13	174	18	42	14.4

In 1968, the U.S. Army committed itself to eliminating postcrash fires in survivable accidents. Prototype crashworthy fuel systems were developed. All helicopters procured by the Army after 1970 were equipped with a CWFS, and an extensive retrofit program was begun for older aircraft. Some of the very encouraging results presented by Knapp, et al. (reference 30) are discussed in the following paragraphs.

During a seven-year period (1970-1976) there were 1,258 survivable U.S. Army accidents for helicopters equipped with a CWFS. Table 34 shows the injury experience in these accidents compared to accidents during the same period for

TABLE 34. COMPARISON OF INJURIES IN U.S. ARMY HELICOPTERS WITH AND WITHOUT CRASHWORTHY FUEL SYSTEMS (REFERENCE 30)

	Survivable		Nonsurvivable	
Classification	W/O CWFS	With CWFS	W/O CWFS	With CWFS
Thermal Injuries	20	5	5	0
Non-Thermal Injuries	529	386	13	28
Thermal Fatalities	34	0	31	1
Non-Thermal Fatalities	120	44	229	85
Accidents	1,160	1,258	61	32
Postcrash Fires	43	16	42	18

non-CWFS-equipped helicopters. To summarize the results of table 34, there were 16 postcrash fires in survivable accidents of helicopters equipped with a CWFS. These fires resulted in five thermal injuries but no fatalities. This compares extremely favorably with 43 incidences of fires and 34 fatalities in aircraft not equipped with a CFWS, and represents a 75-percent reduction in thermal injuries and the total elimination of thermal fatalities.

4.3.5 INJURY DISTRIBUTION BY BODY REGION. The frequency of major and fatal injuries according to body region is compared for civil and Army survivable crashes in figure 30. The most striking difference in this comparison is the greater percentage of spinal injuries for civilian helicopter accidents. There are two factors believed to contribute to this relatively high percentage of spinal injuries.

First, in the civilian accident sample there was a significant number of accidents involving aircraft equipped with lap-belt-only restraint. Reference 8 suggests that the lack of upper torso restraint permits increased spinal misalignment, thus lowering spinal tolerance to vertical acceleration. The magnitude of this effect, however, is difficult to quantify.

The second factor that would contribute to the higher percentage of spinal injury is the older age of the occupants in civilian accidents. Figure 31 compares the age distribution for civilian pilots involved in general aviation accidents and U.S. Army aviators. It was assumed, without the benefit of additional data, that these two distributions approximately represent the occupants that would be involved in these two classes of accidents. The U.S. Army aviators generally fall between 19 and 30 years of age, with a mean age of 26 years. The general aviation pilot group is distributed from 25 to 55 years of age with a mean age of 38 years. The average older age of the civilian flying population predisposes this group to a greater percentage of spinal injuries because bone strength is reduced with age. The results of an analytical study based

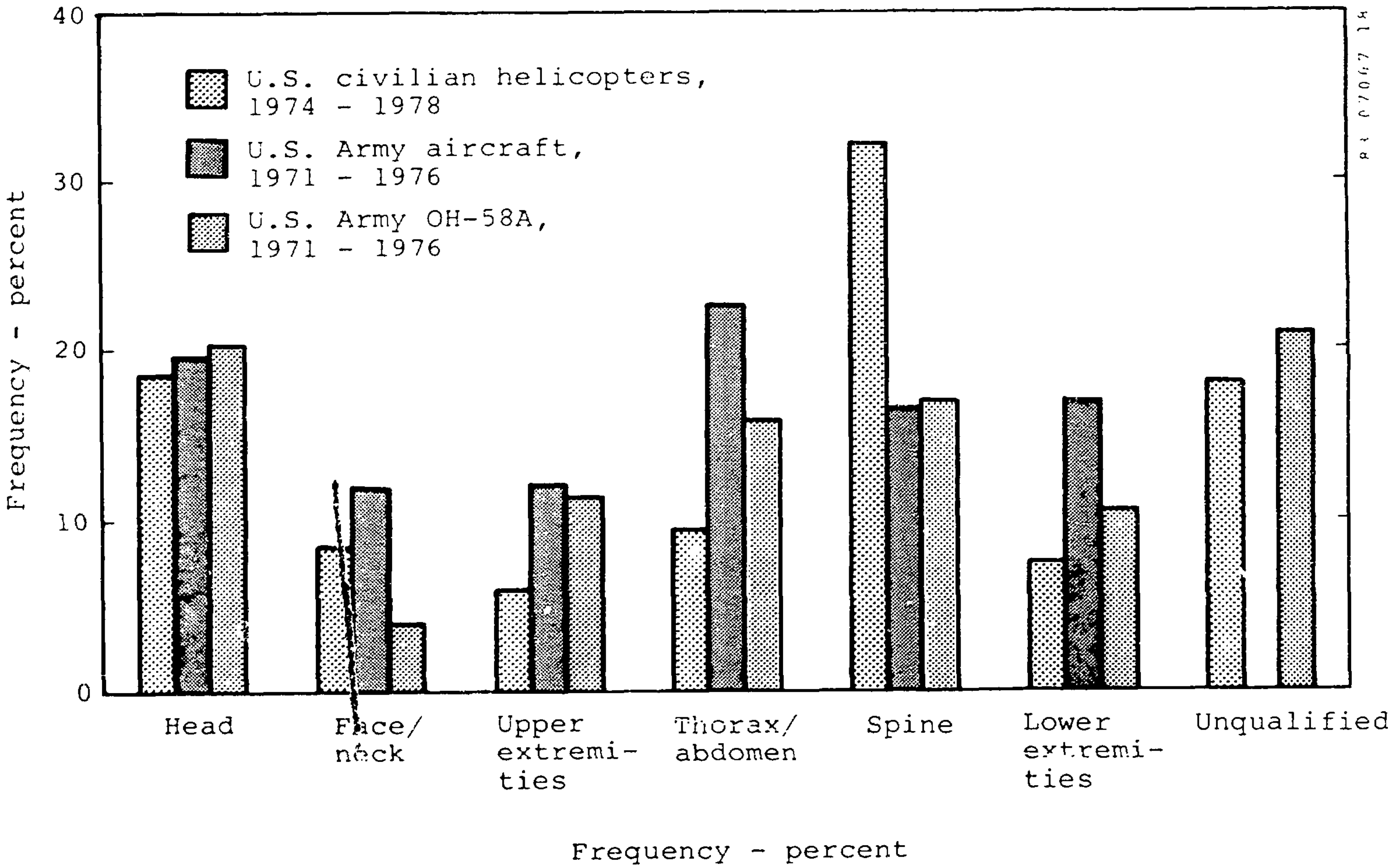


Figure 30. Frequency of major and fatal injuries to each body region as percentages of total major and fatal injuries in survivable accidents.

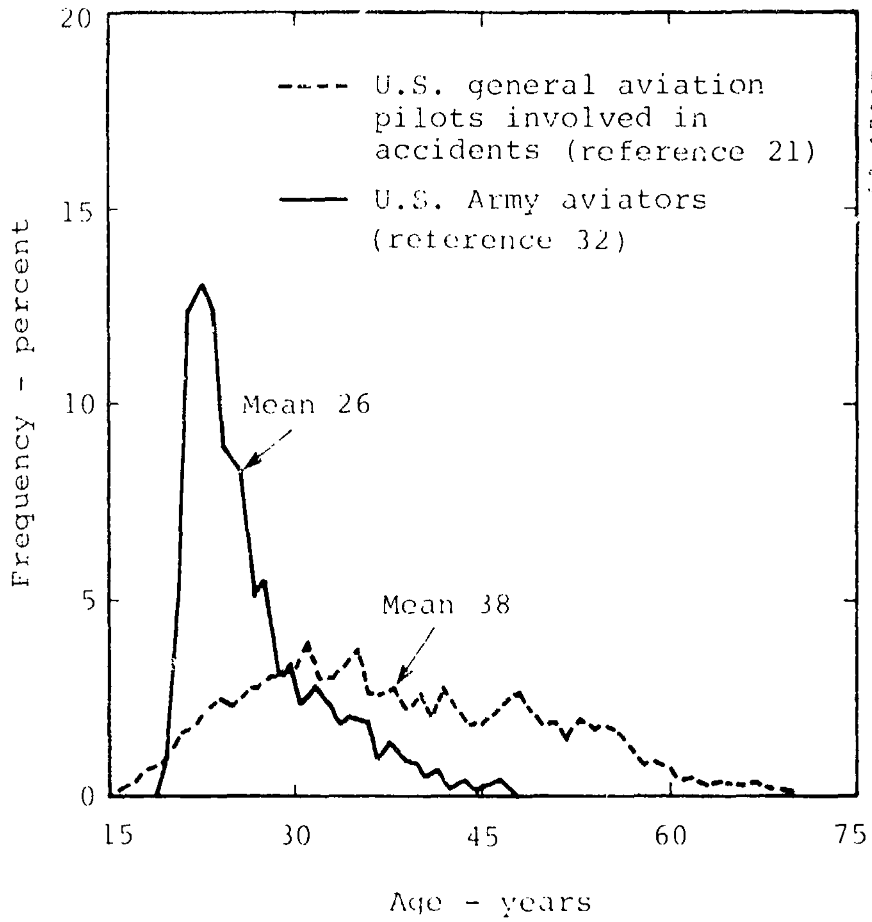


Figure 31. Comparison of the age distributions for U.S. general aviation pilots involved in accidents and for U.S. Army aviators.

on crush tests of vertebral segments are shown in figure 32 (reference 33). The analytical modeling was conducted for a rectangular input pulse, and the curve shown represents the acceleration level that presumably would cause a 50-percent injury rate. Based on the mean ages in the sample distribution, there is approximately a 13-percent reduction in the spinal injury tolerance for the civilian pilot population.

The lower bone strength and spinal tolerance of the civilian helicopter occupants indicates the need to reduce the limit-load factor for civil applications from that used by the Army. Currently, the U.S. Army uses 14.5 G as the limit load for seats in the UH-60A Black Hawk helicopter. Accident experience with this new aircraft is providing validation of this limit load for preventing spinal injuries in Army pilots; however, a limit load in the range of 11.5 to 12.5 G may be more appropriate for civil applications.

4.4 EXISTING CRASHWORTHINESS TECHNOLOGY

The concepts and technology required to implement crashworthiness in civilian helicopters exists today. Most of these concepts were developed for military

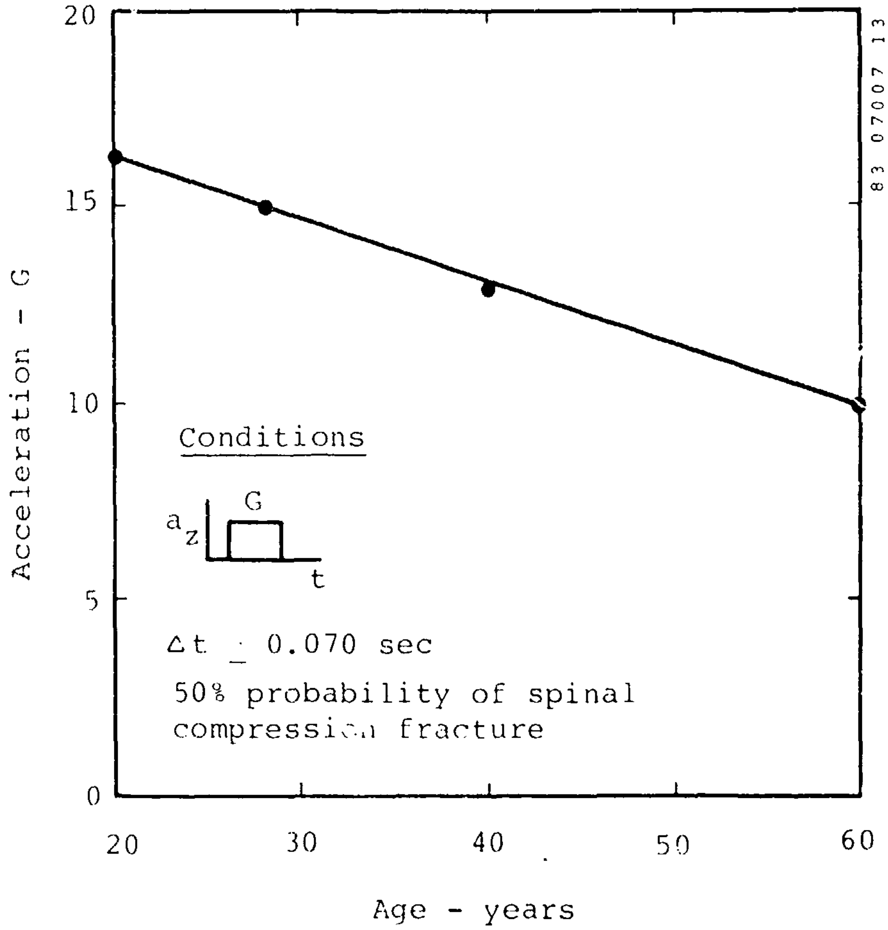


Figure 32. Effect of age on spinal injury tolerance to vertical acceleration (reference 33).

helicopters during the past 15 years, although several civil models incorporated elements of crashworthiness technology. Some aircraft components, such as crashworthy fuel systems, restraint systems, and wire strike protection systems are available as "off-the-shelf" items for retrofit. Many others could be modified to meet the needs of the civil helicopter crash environment. This section discusses some of the current crashworthy technology available in production aircraft and some of the detailed research programs that have recently been completed to aid designers. This is not intended to be a comprehensive list, but rather a sampling of existing capabilities.

4.4.1 CRASHWORTHINESS IN CIVIL HELICOPTERS. Several manufacturers have designed features with crashworthiness capabilities into their aircraft, that exceed the minimum FAR requirements. One such aircraft is the Bell 222, which was conceived and developed to meet the needs of the civilian market. This eight-place, 8,000-lb aircraft was designed for executive travel or offshore oil-rig support. The performance and crashworthiness capabilities of the 222 are described in references 34 and 35.

Seats in the aircraft are designed with static load factors of 8 G forward, 8 G downward; and 4 G in the lateral direction. All positions are equipped with 4-point restraint systems (lap belt and shoulder harnesses). In addition, the crewseats are designed to absorb energy in the vertical direction, providing protection from spinal injury in crashes up to an estimated 25 ft/sec. Dynamic tests have been conducted by the FAA Civil Aeromedical Institute (CAMI) for evaluation of the seat performance (reference 34). The passenger seats are equipped with crushable foam under the seat pan to provide vertical force attenuation. The available 2- to 3-in. crush distance is estimated to provide protection in vertical impacts up to approximately 20 ft/sec.

The fuel system is equipped with four impact-resistant fuel cells. Breakaway fittings are used on the two external cells, located in the wing structure, to minimize the possibility of fuel spillage on impact. Fuel lines have either breakaway fittings or extra length to preclude tearing when the aircraft deforms in an accident. The bladder material and fittings are of the type developed under an FAA-sponsored program to develop a CWFS for general aviation aircraft (reference 36). The bladder material has approximately 10 times the puncture resistance of standard material. Table 35 presents a comparison of the bladder material used in standard, military, and Bell fuel systems.

TABLE 35. COMPARISON OF BLADDER MATERIAL PROPERTIES FOR STANDARD, MILITARY, AND BELL CIVIL CRASH-RESISTANT FUEL SYSTEMS

Test/Description	Standard Bladder US-566RL	Military MIL-T-27422B US-751	Safety Cell US-756
Drop Height With No Spillage	NA	65 ft (full)	50 ft* (80% full)
Constant Rate Tear			
Parallel/Warp	NA	400 ft/lb	210.0 ft/lb
45-degree Warp	NA		
Tensile Strength			
Warp	140 lb	NA	1717 lb
Fill	120 lb	NA	1128 lb
Impact Penetration			
5-lb Chisel			
Parallel/Warp	NA	15 ft	8.5 ft
45-degree Warp	NA	15 ft	8.5 ft
Screwdriver	25 lb	NA	370.5 lb

*Also dropped from 65 ft with no spillage.

Bell has also equipped a number of other models with crash-resistant features. Energy-absorbing seats are available for the 412 and 214ST. A CWFS has been incorporated into the following models: 206 BIII, 206 L-3, 412, 214 B, and 214ST, 222. Table 36 lists the weight penalties associated with the crashworthy features in Bell models. It appears that a 1.0 to 1.5 percent weight penalty will be incurred in attaining the levels of crashworthiness achieved in these Bell models.

TABLE 36. WEIGHT PENALTIES ASSOCIATED WITH CRASHWORTHY COMPONENTS IN BELL HELICOPTER MODELS (REFERENCE 35)

	Models' Weight Penalty (lb)		
	222	412	214ST
Passenger's Shoulder Harness and Energy Attenuating Seats	55	122	161
Crash-Resistant Fuel System	28	35	50
TOTAL	83	157	211
Percentage of Gross Weight	1.1	1.4	1.2

4.4.2 CRASHWORTHINESS IN MILITARY HELICOPTERS. The U.S. military has strongly supported the development of crashworthiness technology. The results of early research programs were used in developing specifications such as MIL-STD-1290 (reference 7) for general crashworthiness, MIL-S-58095(AV) (reference 6) for energy-absorbing seating, and MIL-T-27422B (reference 37) for crash-resistant fuel systems. The latest revision of the U.S. Army Aircraft Crash Survival Design Guide (references 1 through 5) contains design criteria for Army aircraft based on research conducted up to 1979.

The U.S. Army has retrofitted a number of crashworthy components into older helicopters, such as CWFS in most helicopter models, and energy-absorbing crewseats and cargo restraints in the CH-47. However, the true test of the system crashworthiness capabilities will be in the new generation of military helicopters: the U.S. Army's UH-60A Black Hawk and AH-64A Apache, and the U.S. Navy SH-60B Seahawk. The crashworthiness capabilities of these aircraft are discussed in references 38 and 39.

The Army conducted a full-scale crash test of a YAH-63 helicopter to validate the criteria contained in the specifications discussed above (reference 40). Validation of these design concepts has also occurred through the accident experience of the UH-60A aircraft. A remarkable degree of protection has been exhibited in several extremely severe accidents (references 41 and 42).

In an effort to continue refining the crashworthy subsystem design process, the U.S. military has sponsored several recent studies. Sikorsky was engaged

to conduct a sensitivity analysis of the life cycle costs associated with four levels of crashworthiness in several helicopter designs: a metal Medium Utility Transport helicopter (MUT), a metal Army Scout Helicopter (ASH), and a composite Army Scout Helicopter (reference 43). The Army contracted with Bell and Sikorsky to develop the technology required to provide crashworthiness (to the levels contained in MIL-STD-1290) in all composite helicopters (references 44 and 45). The technology developed in the Advanced Composite Airframe Program (ACAP) is directly applicable to 8,000- to 9,000-lb class civil aircraft. References 46 and 47 discuss developments in the ACAP effort. Simula Inc. has recently conducted two programs sponsored jointly by the Army, Navy, FAA, and Air Force. These programs investigated the sensitivity of design parameters in energy-absorbing seating systems and the spinal fracture tolerance level of cadavers in energy-absorbing seats (references 48 and 49).

4.4.3 CRASH-RESISTANT COMPONENTS. A number of crash-resistant components are available through the commercial accessory market. For example, Robertson Aviation, Inc. produces crash-resistant fuel systems for the Hughes 500, and Bell 206. In addition, this company also has designs available for primary crash-resistant fuel systems that were derived from military models manufactured by Hughes, Bell, Boeing-Vertol, and Sikorsky. Canada's Bristol Aerospace Ltd. manufactures wire strike protection systems, distributed by Aeronautical Accessories Inc., for the Bell 204, 205, 206, 212, 214, and Hughes 500. High-strength commercial restraint systems are available from American Safety, Davis, and Pacific Scientific. This list is by no means complete, and it is presumed that other manufacturers produce similar crash-tolerant components.

5.0 CONCLUSIONS

This study was funded to provide a data base to support FAA rule-making efforts. Three hundred and eleven accident reports from the five-year period of 1974 to 1978 contained sufficient information to warrant examination. For the accidents in which sufficient documentation existed, the crash sequences were carefully reconstructed to determine the crash environment. The result is a data base containing statistical descriptions of the distribution of impact angles and velocities. The data were compiled for four weight classes, although it was found that there was very little difference between weight classes in any of the investigated parameters.

It was found that, in the typical rotorcraft accident, the pitch, roll and yaw angles were small. For example, 71 percent of the rotorcraft impacting the ground had pitch angles of ±20 degrees or less. Correspondingly, the percentages of accidents with roll and yaw angles below ±10 degrees were 72 percent and 88 percent, respectively. The impact velocities developed in this study were based on 154 significant survivable accidents. Based on a statistical summary of these accidents, the 95th-percentile severe survivable vertical, longitudinal, and lateral velocity components were found to be 26 ft/sec, 50 ft/sec and 10 ft/sec, respectively. Although many serious injuries and fatalities occurred in accidents with velocities below the 95th-percentile level, these conditions were found to reasonably represent the upper limits of survivability in the rotorcraft fleet examined.

Six crash scenarios were developed to represent the various type of accidents which were identified in the study. These six scenarios included approximately 69 percent of the accidents surveyed. The specific scenario types were: vertical impact, longitudinal impact, rollover, wire strike, water impact, and high yaw rate impact. In terms of the number of injuries occurring in accidents of each type, the vertical impact scenario was the most hazardous. Both the water impact and wire strike scenarios were found to produce significant numbers of injuries. The other three scenarios were found to be much less hazardous.

The civil crash environment characteristics were compared to those determined for military helicopters. It was found that military design velocities (which were derived from a study similar to this one) in the vertical and lateral directions were more severe than those of the civil accident data. Based on this comparison, it was determined that current military design criteria would be too stringent for civil rotorcraft. Section 6.0 presents recommended design criteria based on the civil crash environment identified in this study.

The crash force magnitudes imposed on an occupant in the recommended design crash environment were compared to levels of human tolerance. It was found that, for a well-restrained occupant, only the vertical impact forces exceeded the levels expected to produce serious injuries (mainly spinal injuries). This indicates a need to require vertical energy absorption in the landing gear, airframe, or seats to maintain a tolerable environment for the occupants. In the longitudinal and lateral directions, the crash environment is not expected to produce decelerative loadings that exceed tolerable levels for a properly restrained occupant. Energy-absorption techniques may be used in these directions to enable the airframe to sustain the impact forces; however, energy-absorption within the seat or restraint system is not necessarily desirable

because it would expand the occupant strike envelope and increase the chances of secondary impact within the cockpit.

This study also included an analysis of injuries and injury-causing mechanisms in accidents occurring during the 1974 to 1978 period. Ninety-four out of 132 survivable accidents occurring during this period contained injury descriptions. From this information it was possible to identify 14 hazards, or injury-causing mechanisms, that were present in the civil crash environment. These 14 hazards were ranked according to their frequency of occurrence and the severity of injuries that were produced. It was found that there were four predominate hazards that could be addressed to improve civil rotorcraft crashworthiness. These hazards include: thermal injuries from postcrash fire, failure of the restraint system to protect against secondary impact, excessive vertical impact loads transmitted to the occupant, and inflight wire strikes which result in uncontrolled flight.

The numbers and severities of injuries in "survivable" civil rotorcraft accidents indicate the need for improved design requirements. For example, based on an average yearly rate of the five years examined, approximately 40 percent of the survivable accidents had injuries and/or fatalities. There were 545 occupants involved in survivable rotorcraft accidents. Out of these 545 occupants 23 were fatally injured, 57 received serious injuries, and 95 sustained minor injuries. It is these fatalities and injuries which occur in survivable accidents that crashworthiness improvements can help to alieviate.

The data presented in this report provide a comprehensive analysis of the state of crashworthiness existing in current rotorcraft models. This study could provide the basis for initiating a review of applicable rotorcraft regulations FAR Part 27 and Part 29.

6.0 RECOMMENDATIONS

The data developed in this study indicate a need for improved crashworthiness in U.S. civil rotorcraft. This need is based on the number of serious injuries and fatalities that occur in accidents judged to be survivable in the current rotorcraft fleet. The technology exists to reduce significantly the number and severity of these injuries in future aircraft through crashworthiness improvements. However, the justification for these improvements from a cost standpoint has not been investigated. The costs, and resulting benefits, will be directly related to the degree of protection sought. Even without considering the economics of these improvements the data in this study suggests an upper limit to the degree of protection. This level of protection coincides with the most severe impact conditions found to occur for civil helicopters. Obviously, there will be some cost-effective level of protection between the existing fleet technology level and the maximum necessary to provide complete protection to all occupants.

As noted above, the crashworthiness technology does exist to achieve even the maximum level of protection. The state-of-the-art is continually being advanced for military aircraft. However, crashworthiness has never been incorporated universally in the competitive aircraft marketplace. The approach taken by the FAA to bring about improvement, should be both assertive and cautious. From the assertive standpoint, the FAA must perceive the need for crashworthiness improvements and conduct whatever programs are necessary to verify this need. At the same time, a cautious approach needs to be taken in setting the level of crashworthiness protection to be achieved. Although many of the major U.S. helicopter manufacturers possess the capability to design crashworthiness into their aircraft, the learning curve for all civil manufacturers will be steep to incorporate it in a cost-effective manner.

The current focus should be to develop design criteria based on a responsible assessment of the civil crash environment. The manufacturers will need a set of design criteria to investigate the ramifications involved in incorporating improved crashworthiness. Concurrently, the FAA needs to provide R & D money to develop key technologies and cost-effective approaches to meet the proposed levels of protection. The remainder of this section presents a suggested set of design criteria based on the identification of the civil crash environment. Recommendations for future work to be conducted under FAA sponsorship are also included.

6.1 CRASHWORTHINESS DESIGN CRITERIA FOR U.S. CIVIL ROTORCRAFT

The recommended approach presented in this paragraph is based on providing protection up to and including the 95th-percentile survivable crash environment identified in Section 3.0. An argument could be made to base the design criteria on the 95th-percentile impact conditions (which includes both survivable and nonsurvivable accidents). Using this approach, the design criteria would be related to accident kinematics and not to survivability levels in the existing helicopter fleet. However, the 95th-percentile survivable level of protection appears to be both reasonable and attainable within the development period of the next generation of commercial helicopters.

6.2 IMPACT VELOCITY COMPONENTS

Design impact velocities for certification of new rotorcraft models are based on the 95th-percentile survivable level of accidents evaluated for the 1974-78 period. Table 37 lists the design velocity components for new models. The intent is to reduce the number of fatalities and the severity of injuries in survivable accidents.

TABLE 37. RECOMMENDED DESIGN VELOCITY CHANGES FOR CERTIFICATION OF NEW MODELS

Direction Along Aircraft Axis	Design Velocity Change (ft/sec)
Vertical (Downward)	26
Lateral	10
Longitudinal (Forward)	50

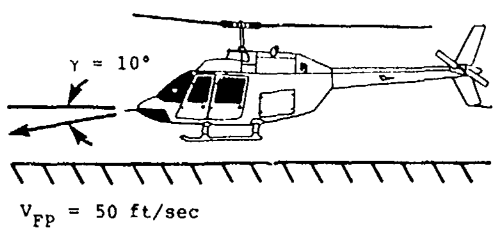
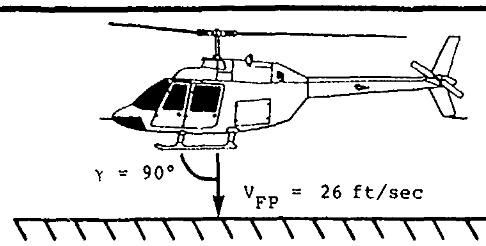
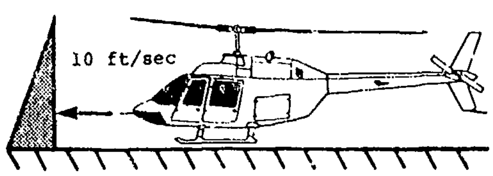
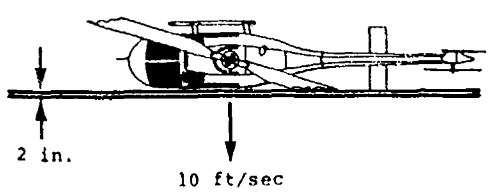
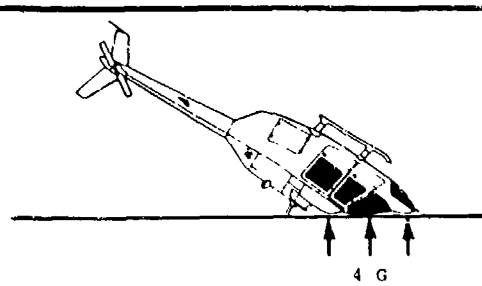
The velocity components presented in this section are characteristic of the aircraft kinematics prior to impact. This does not provide sufficient information for design purposes. The velocity change in the principal impact, deceleration pulse, and aircraft attitude are all required to specify design criteria. Recommended values of these parameters are suggested in the following paragraphs.

6.3 IMPACT PULSE DECELERATION CHARACTERISTICS

Five design conditions were developed to provide general airframe requirements for protection in severe, but survivable, accidents. These conditions represent a significant portion of the accidents that were evaluated in this study. Figure 33 illustrates the five conditions applicable to the design of new rotorcraft.

The impact conditions specified in numbers 1 and 2 relate to the velocity components for the 95th-percentile survivable impact level. These two conditions will be the major tests of the energy absorption system and anti-plowing capability of the airframe. In addition, the acceleration environment produced by these impact conditions will affect the design requirements for internal aircraft components.

The first two conditions will, undoubtedly, have the greatest effect on structural design. Impact conditions 3, 4, and 5 are based on "packaging" considerations for the occupants. Although they are less severe overall for the airframe, the localized loads produced by these impact conditions are important for preserving livable volume within the cockpit and cabin areas.

Condition Number	Impact Condition*	Impact Surface	Intent
1		Soft ground	High-speed, run on landing. Major impact deforms/removes gear, damages fuselage understructure. "Plowing" of fuselage should be prevented.
2		Hard, smooth surface	Pure vertical impact. All energy-absorption capability of gear depleted. In order to minimize hazard to occupants, fuselage understructure and/or seats must attenuate deceleration pulse. Overhead structure and high mass items must stay in place.
3		Rigid obstacle	Sliding aircraft encounters rigid obstacle. Airframe must be strong enough to prevent structural deformation that impinges on occupants. Less than 15 percent reduction in cockpit volume is desirable.
4		Soil or water. Aircraft buried 2 in.	Impact in 90-degree roll attitude to either side. Contact forces distributed over buried airframe surface. Internal volume should not be reduced by more than 15 percent.
5		Soil. Aircraft buried 2 in.	Frontal plane of cockpit impacts ground as aircraft flips end over end. 4-G load distributed over airframe structure (not canopy) buried in ground. Intrusion into livable volume of cockpit should be minimized.

*γ = flight path angle.

V_{FP} = Flight Path Velocity.

84 01004 44

Figure 33. Recommended airframe design impact conditions for newly certificated rotorcraft models.

6.4 LANDING GEAR*

Landing gear play an important role in the overall energy absorption system of an aircraft. In crashes of aircraft with relatively flat impact conditions, the gear deform while slowing aircraft vertical velocity. It was determined in this study that the gear may have functioned in 53 percent of the accidents. In the remaining 47 percent of the accidents, either the terrain type (such as water), terrain features, or impact attitude rendered the gear ineffective. Considering the percentage of accidents in which the gear actually functioned, a significant amount of the vertical energy-absorption capability, which is needed to provide tolerable acceleration levels for the occupants, should be placed in other system components. These components include the underfloor structure and seating systems. On the other hand, increased gear energy absorption capability would prevent fuselage/ground contact in a large number of less severe accidents. The savings in structural impact damage may make increased gear capabilities advantageous. The following methodology is suggested for setting energy-absorption requirements for landing gear.

An analysis of rotorcraft conforming to FAR Part 27 indicates that the 10.23 ft/sec reserve energy sink speed provides approximately 15.5 percent of the energy absorption capability required to dissipate the 95th-percentile vertical impact speed of 26 ft/sec. This is based on the ratios of kinetic energy at impact, i.e.,

$$\text{Percent of E/A capability} = \frac{\frac{1}{2}\,m\,V_{RE}^2}{\frac{1}{2}\,m\,V_{95}^2} = \frac{(10.2\text{ ft/sec})^2}{(26.0\text{ ft/sec})^2} = 15.5\text{ percent}$$

A similar calculation for military aircraft complying with MIL-STD-1290 indicates that 20-ft/sec gear would dissipate approximately 22.7 percent of the 42-ft/sec design speed. It is believed that the energy-absorption requirements should fall in the 15 to 23 percent range. The exact gear capability within this range should be left as an option to the designer with the provision that the overall vertical energy-absorption system be able to dissipate the 95th-percentile design impact speed in a tolerable manner.

6.4.1 Vertical Energy-Absorption Requirements. Landing gear should be designed to provide maximum sink speed capability of between 15 and 23 percent of the impact kinetic energy for the design vertical impact velocity of 26 ft/sec. The design should be based on maximum aircraft gross weight, a 2/3-G rotor lift factor, and symmetric, vertical impact. The recommended maximum sink speed is 12.0 ft/sec.

The effectiveness of the landing gear energy-absorption capability must be verified. It is recommended that a vertical drop test be conducted simulating a

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* This section deals primarily with fixed landing gear. The experience with retractable gear under crash conditions is limited; hopefully this subject will be addressed in future work.

zero roll and pitch attitude at impact using a jig drop test for wheeled gear and a weighted frame drop test for skid gear. The performance of gear at various roll and pitch angles should be verified analytically or by dynamic testing. The requirements for landing gear off-axis performance are described in the following section.

6.4.2 Landing Gear Performance Envelope. It is recommended that landing gear should be designed to function within the envelope shown in figure 34a. The required design vertical sink speed for the gear is indexed to the roll angle due to the trend of lower impact speeds with increasing roll angle, shown in figure 18. The recommended design sink speeds for the roll-angle range is shown in figure 34b.

6.5 SEATING SYSTEMS

Seating systems in rotorcraft meeting the proposed requirements outlined in this chapter should perform three functions: reduce vertical impact loads transmitted to the occupant to tolerable levels, provide strength in the longitudinal and lateral directions to resist inertial forces, and protect the occupant from secondary impact. The vertical energy absorption capability should complement the landing gear design so that the overall energy absorption system meets the design requirements. In the longitudinal and lateral directions, the seat should provide the ability to resist dynamic loads without failure. Energy absorption in these directions is not necessary, or desirable, because it enlarges the occupant strike envelope within the cockpit or cabin. It is recognized that in some cases, especially in modifying existing airframe designs, use of load-limiting seat attachment devices may be necessary to prevent failure of the airframe under crash loading.

As discussed in section 4.3.5, current military energy-absorbing seats are based on a 14.5-G limit-load factor for the 50th-percentile occupant weight. Considering the age distribution for civil versus military pilots, as shown in figure 31, and the reduction in bone strength that occurs with increasing age, a limit-load design factor of 12 G is recommended for civil applications. It is believed that a significant percentage of occupants involved in rotorcraft accidents are adult males. Until conclusive data are available, it is recommended that the weights listed in table 38 be used for design purposes.

6.5.1 Seat Design Requirements for New Rotorcraft. Cockpit and cabin seats should be designed to provide vertical energy absorption and unimpeded stroke distance*. An energy absorber limit-load factor of 12 G ± 1 G is recommended. For fixed-load energy-absorbing systems, the limit load should be calculated according to the following equation:

$$\text{Design Limit Load} = 12 \times \begin{matrix}\text{50th-percentile Male}\\ \text{Occupant Vertical}\\ \text{Effective Weight}\end{matrix} + \begin{matrix}\text{Movable}\\ \text{Seat}\\ \text{Weight}\end{matrix}$$

*Underseat items should not be allowed to enter this restricted space.

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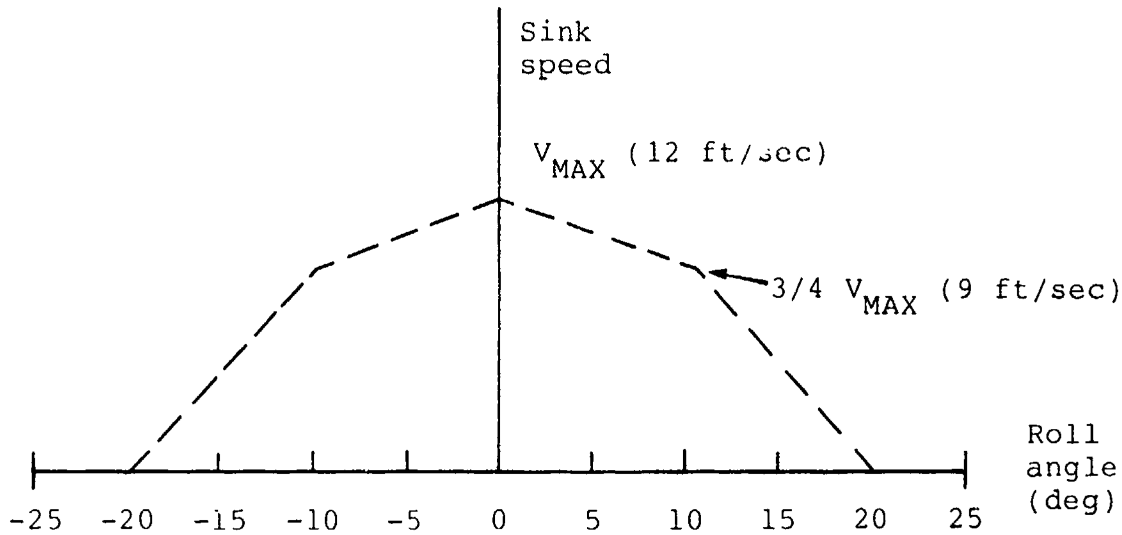
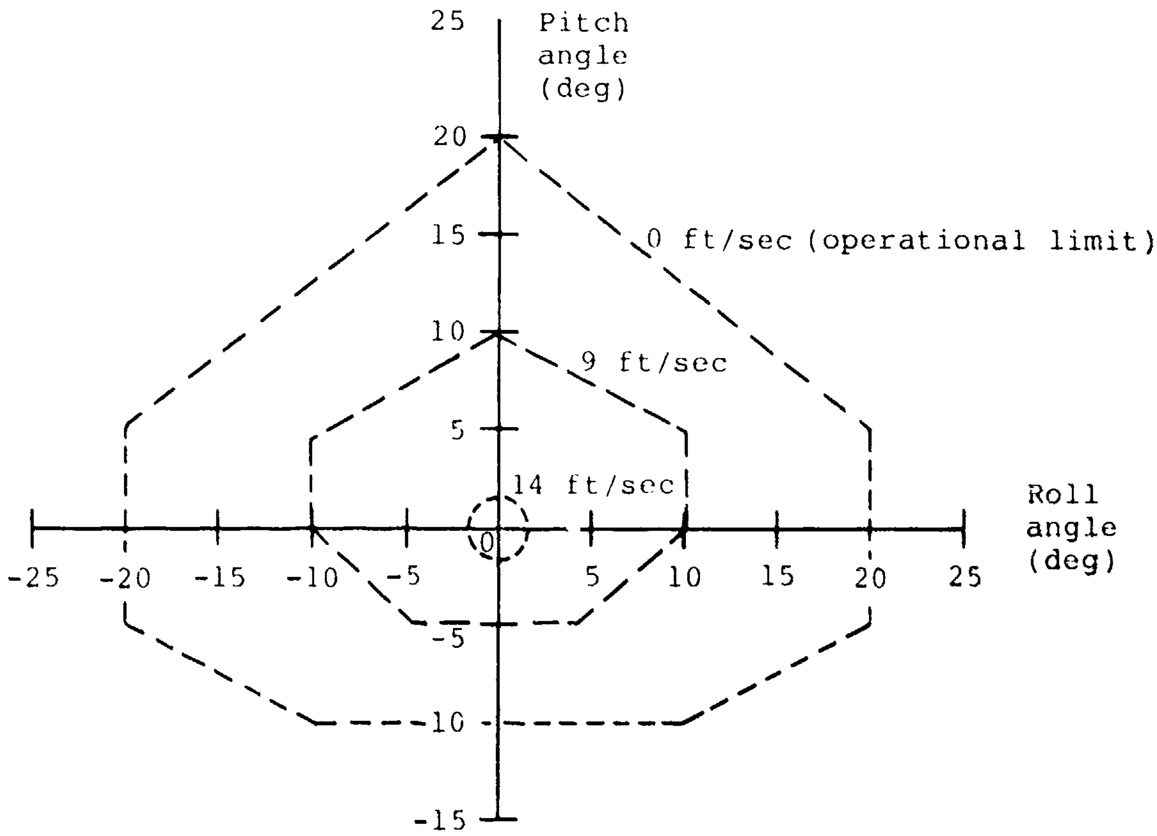


b. Design sink speed as a function of roll angle, based on maximum sink speed V_{MAX}. (Recommended values shown in parentheses).



a. Pitch and roll axis envelope

Figure 34. Landing gear design requirement envelopes.

TABLE 38. RECOMMENDED DESIGN WEIGHTS BASED ON U.S. CIVILIAN POPULATION (FROM REFERENCE 50)

Description	Design Weight* (lb)	Vertical Effective Weight (lb)
95th Percentile U.S. Adult Male	217	174
50th Percentile U.S. Adult Male	166	133
5th Percentile U.S. Adult Male	127	102
50th Percentile U.S. Adult Female	136	109

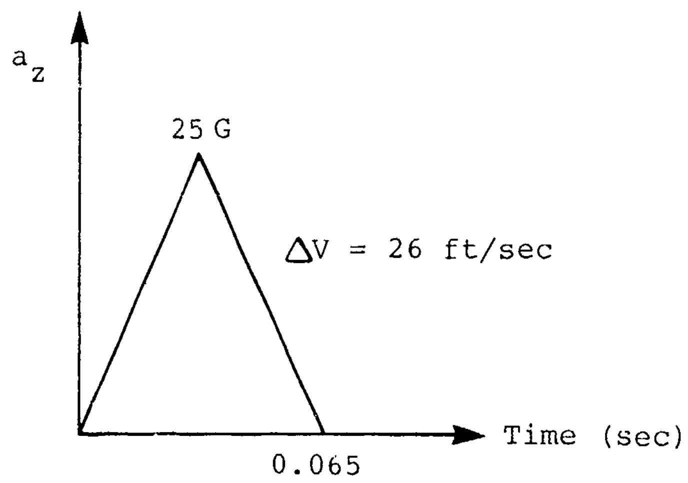
*Lightly clad, clothing weight 3 lb.

It is desirable to incorporate variable-load energy-absorbing devices to account for the wide range of occupant weights for the civil population.

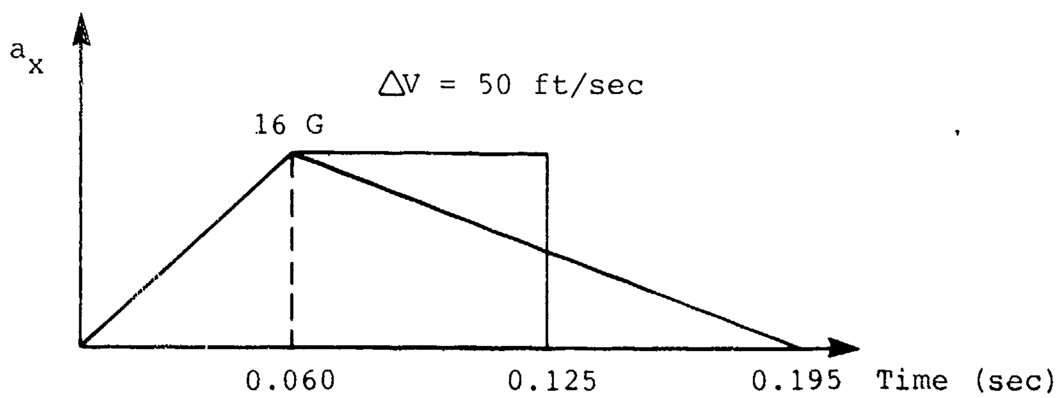
The airframe design impact conditions presented in paragraph 6.2 provide requirements for seating-system capability. Condition number 2, a purely vertical impact, places requirements on the vertical energy absorption. It is recommended that the vertical velocity change not be reduced by the landing gear velocity increment. The landing gear will not function on some vertical impacts and/or the gear may be retracted. The recommended vertical deceleration pulse for seat design is shown in figure 35a.

In the longitudinal direction, it is recommended that the design deceleration pulse for seats in the longitudinal direction meet three specific requirements: 250-G/sec onset rate, 16-G peak, and 50-ft/sec velocity change. Figure 35b shows several possible pulse shapes that meet these requirements.

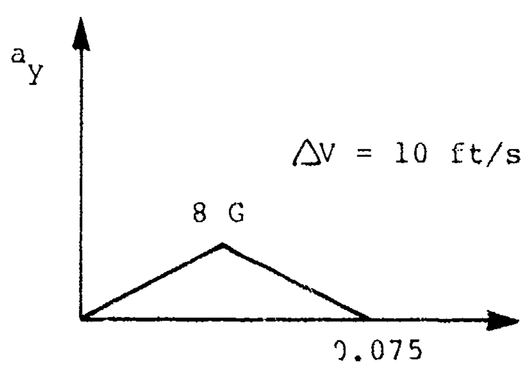
The lateral seating system design requirements are based on the most severe demands from rollover-type accidents or vertical impacts with a significant roll angle. Figure 35c shows the worst recommended lateral design condition. The seat stroke necessary to meet the vertical seat deceleration pulse, figure 35a, was estimated from test data described in reference 48. Figure 36 shows the estimated seat stroke for various vertical velocity changes and occupant sizes. For the vertical design requirement of 26 ft/sec with the recommended 12-G design limit load, the 50th-percentile occupant would need approximately 3.8 in. of vertical stroke. Similarly, the 95th-percentile occupant would need 4.5 in. of vertical stroke capability.



a. Vertical deceleration pulse



b. Longitudinal deceleration pulses



c. Lateral deceleration pulse

Figure 35. Recommended dynamic deceleration conditions for seating system design.

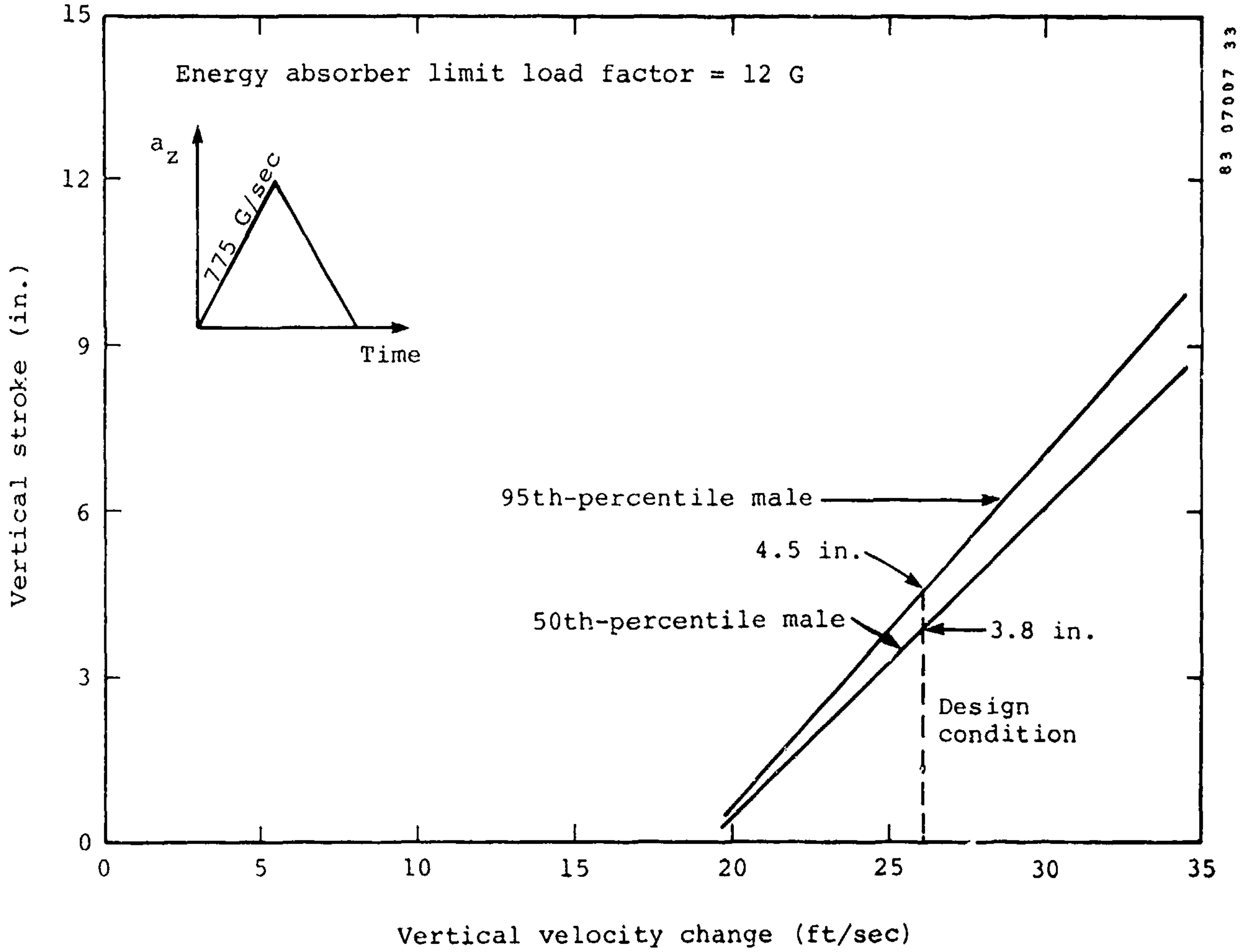


Figure 36. Vertical seat stroke requirements for 50th- and 95th-percentile male occupants.

6.5.2 Static and Dynamic Seating System Test Requirements. Two types of testing are recommended to verify seat performance under crash loading. Static (or quasi-static) loading validates the design concept and static structural analysis modeling. Static testing is not a substitute for dynamic crash tests which prove the performance under rapid loading and dynamic load magnification caused by overshoot.

Table 39 lists the dynamic load factors (in multiples of effective weight, or G's) recommended for validating seating system design. The effective weight in each direction is the listed design occupant weight plus the appropriate seat weight. The seating system should be capable of sustaining the applied loads without failure of components that would jeopardize the retention capability of the occupant or seat performance. Static loads should be applied in a distributed manner that simulates inertial loading. Loads for the upward, forward, and lateral conditions should be applied through a body block (rigid torso segment) that distributes the load to the seat through the restraint system.

TABLE 39. SEAT DESIGN AND STATIC TEST REQUIREMENTS

Test Ref. No.	Loading Direction With Respect to Fuselage Floor	Load Factor Required	Percentile Occupant Used in Load Determination	Conditions
1	Upward	6-G minimum	95	
2	Downward	12 ± 1 G	50	Controlled Deformation
		25-G minimum	50	Subsequent to controlled deformation
3	Aftward	10-G minimum	95	
4	Forward	20-G mimimum	95	
5	Lateral	10-G mimimum	95	

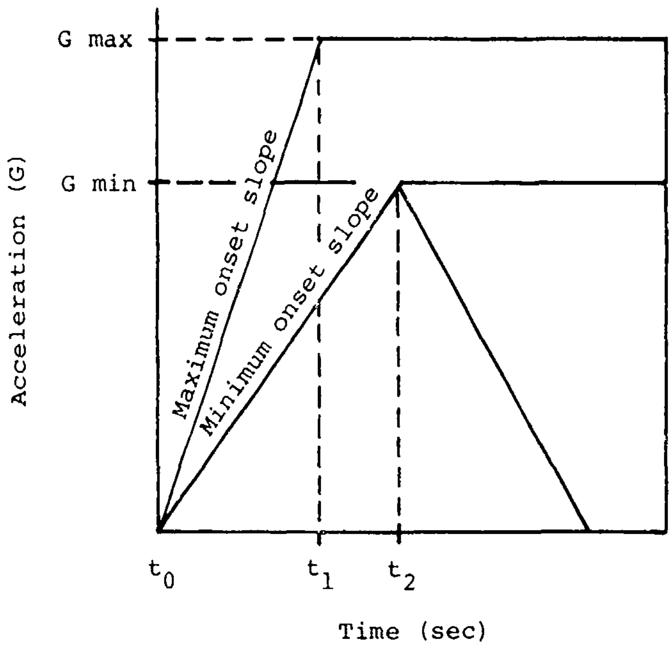
Two dynamic tests are recommended for validating performance of seats under realistic impact conditions. Figure 37 shows the two test requirements. Test 1 is designed to exercise the vertical energy-absorption system in the presence of longitudinal and lateral load vectors. The second test is intended to demonstrate that the seating system can retain the occupant under high longitudinal and lateral dynamic loading. For each test condition, tolerances are provided for the peak deceleration and associated time duration. The offset slope is not defined because it is difficult to control in testing, and it has little overall effect on performance.

6.6 RECOMMENDATIONS FOR FUTURE WORK

The following paragraphs describe general tasks recommended for future funding by the FAA. These tasks would provide a data base to support improved crashworthiness requirements in FAR Parts 27 and 29.

- Detailed Design Criteria/Design Guide

  The recommended design criteria contained in Chapter 6 of this report should be expanded in detail to include all aspects of rotorcraft design. Table 40 lists areas that should be addressed in developing comprehensive design criteria. The outcome of this work could be two reports in advisory circular formats: one containing recommended modifications to FAR Parts 27 and 29, and a design guide comparable to the U.S. Army's Aircraft Crash Survival Design Guide, containing technology appropriate for the civil rotorcraft crash environment.



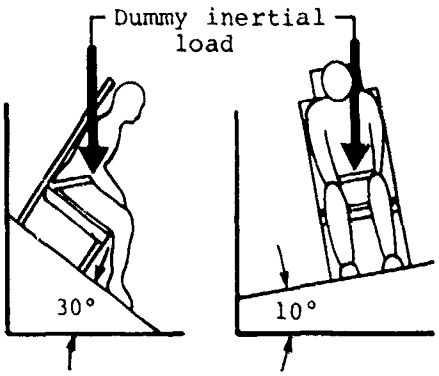
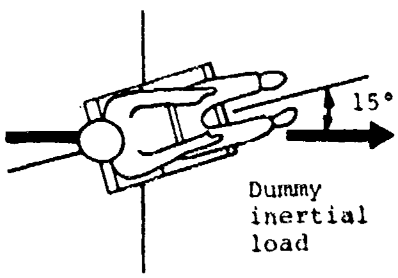
Test	Configuration	Parameter	Magnitude
1		t_1 sec t_2 sec G min G max Δv min, ft/sec	0.030 0.040 27 31 30
2		t_1 sec t_2 sec G min G max Δv min, ft/sec	0.055 0.070 16 20 50

Figure 37. Dynamic test requirements for qualification of seating systems.

TABLE 40. AREAS TO BE ADDRESSED FOR DEVELOPMENT OF DETAILED DESIGN CRITERIA

1.	Human tolerance criteria.
2.	Crash resistant fuel systems.
3.	Airframe structural design.
4.	Vertical energy absorption system.
5.	Energy-absorbing seating systems.
6.	Anthropometry of rotorcraft occupants.
7.	Landing gear design.
8.	Restraint system design.
9.	Retention strength for high-mass items.
10.	Retention strength for ancillary equipment.
11.	Cargo tiedown restraints.
12.	Delethalization of interior (including flammability).
13.	Postcrash egress.
14.	Ditching/flotation characteristics
15.	Wire strike protection.

- <u>Prototype Crashworthy Rotorcraft Demonstration Project</u>

  The FAA should support development of a prototype crashworthy helicopter (possibly modification of an existing model) to demonstrate the feasibility of incorporating the recommended design criteria. The precedents for this type of project are the AG-1 prototype agricultural aircraft project sponsored by the CAA in 1950 and the Experimental Safety Vehicle (ESV) automotive program sponsored by the Department of Transportation in the early 1970's. The demonstration project could culminate with full-scale crash tests to validate the design technology.

- <u>Cost/Benefit Analysis</u>

  The goal of this task would be to examine costs associated with civil rotorcraft accidents and benefits associated with providing various

degrees of crashworthiness protection. This report recommends that the 95th-percentile survivable crash environment of current rotorcraft models be used as the basis for design requirements in future models. A cost/benefit analysis could suggest a more appropriate level for incorporation of minimum design standards.

- Enhancement of Analytical Methods

  A program should be initiated to correct deficiencies in the analytical techniques described in Appendix A. In some cases, these programs could be modified to meet the needs of rotorcraft design. These analytical methods would be used to support the Prototype Crashworthy Rotorcraft Demonstration Project. The applicability to the certification process should also be investigated.

- Improved Crash Investigation Procedures

  The techniques and procedures for documenting rotorcraft accidents should be improved. The National Transportation Safety Board (NTSB) has addressed this issue in recent years. Improvements are necessary in collecting data suitable for crash kinematics reconstruction, in evaluating factors affecting human survivability, and in tabulating injury types and severity. Improved accident reporting forms and continued training for investigators should be the subject of this task.

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APPENDIX A

ANALYTICAL METHODS FOR ROTORCRAFT CRASHWORTHINESS EVALUATION

Analytical methods are available for the crashworthiness evaluation of aircraft structures and seats. Although static, linear elastic structural analyses are conducted routinely throughout the industry, crashworthiness analyses reside generally in the realm of applied research. Nonlinear, dynamic structural analyses are generally expensive to run, and a significant degree of engineering judgement is required in model development. Occupant simulations have become commonplace in the automobile industry for evaluation of restraint systems and vehicle interiors, but the models used there do not represent the seat in sufficient detail to be useful in aircraft crashworthiness analysis.

The following sections describe structural analysis methods, and seat/occupant models, emphasizing available, validated tools.

A.1 STRUCTURAL ANALYSIS

Analysis of the crash behavior of aircraft structures is complicated by the complex nonlinear material and geometric nature of the structural response. Large deflections and rotations in the deformed structure, regions of intense curvature (wrinkling), material strain rate effects, and interference and contact among structural components during the response are some of the difficulties found in modeling the crash response of aircraft structures.

This section presents the requirements for analytical models to be used in crash analysis of aircraft structures as well as evaluations of available crash dynamics computer programs.

A.1.1 REQUIREMENTS FOR ANALYTICAL MODELS. Simulation of aircraft structures in a crash environment requires analytical models that can produce sufficiently accurate results within acceptable time and cost constraints. From an economic standpoint, it is desirable to develop the simplest analytical model of the structure feasible with the required level of accuracy. A question to be answered then is how detailed a model is required within the constraints of economic viability.

The purpose of crash simulations can be grouped into two major categories:

1. Evaluation of gross vehicle response, design trends, structural design and impact parameters, and gross energy dissipation.

2. Analysis of designs where the detailed behavior of individual components is critical, obtaining loads required for input to other analyses, and detailed stress analysis in sizing structural components.

It is usually not cost effective and/or accurate to use the same analytical model for both of these purposes.

Hybrid models that combine experimental and numerical methods in which the structure is divided into a number of relatively large sections or subassemblies

are cost effective and sufficiently accurate for evaluation of gross vehicle response. The sections and subassemblies are treated as lumped masses and nonlinear beam and spring elements. The crash behavior of each of these components is determined externally by test or separate analysis.

Finite element models that employ more formal approximation techniques in the discretization of the structure and rely on the fundamental principles of structural mechanics are required for analyses where the detailed response of individual components is desired. The stiffness characteristics of the individual elements are calculated internally and depend interactively on the loading path, material properties, and the changing shape and position of the structure. Currently available computer programs that utilize hybrid and finite element models of the aircraft structure are described in paragraph A.1.2. While an accurate and versatile computer program is essential for an adequate crash analysis, particularly for hybrid models, some expertise in modeling a vehicle for nonlinear dynamic analysis is also necessary. A thorough understanding of the theory, as well as sufficient experience, is required by the analyst who prepares the model and its input data for the computer program.

A.1.2 EVALUATION OF AVAILABLE PROGRAMS. A number of computer programs for analysis of aircraft structures in a crash environment have been developed and some of these have begun to find use in the design process. The more significant programs have been critically reviewed recently by several authors, including Saczalski (reference A-1), Hayduk, et al. (reference A-2), McIvor (reference A-3), and Kamat (reference A-4). These programs, representing different levels of capability and applicability, can be grouped into two main classes:

1. Hybrid programs.

2. Finite element programs.

Hybrid-type programs require structural component crush data derived from tests or separate analyses as input data. Several simple hybrid simulation programs are available (references A-5 through A-11). The vehicle is represented by one to ten lumped masses and up to 50 degrees of freedom. Large structural assemblies are modeled as nonlinear springs. The two most notable of these programs are those authored by Gatlin, et al. (reference A-10) and Herridge and Mitchell (reference A-11). The work done by Herridge and Mitchell is oriented towards automobile crash impacts, while the Gatlin program (CRASH) simulates the vertical crash impact of the helicopter fuselage modeled with rigid masses connected to nonlinear axial and rotary springs in a predetermined arrangement. These simulations are two-dimensional.

More advanced hybrid programs employ beam and spring elements and lumped masses at the intersection of beam elements in either two-dimensional or three-dimensional configurations. Typical of the advanced hybrid programs are those developed by researchers at Lockheed-California (reference A-12), Calspan (reference A-13), Philco-Ford (reference A-14), and Chrysler Corporation (reference A-15). In the aircraft industry, program KRASH, developed at Lockheed-California by Wittlin, et al., is the most widely used advanced hybrid crash simulation program.

Finite element programs attempt to surpass the limitations of the lumped-parameter approach of the hybrid programs by employing more formal approximation

techniques in the discretization of the structure and a greater reliance on the fundamental principles of structural mechanics. The limitations of the finite element approach are found in the inherent tendency toward more complicated and expensive computations and difficulties found in modeling the extensively complex phenomena, such as large deflections and rotations in the deformed structure, regions of intense curvature (wrinkling), material strain rate effects, and interference and contact during the response, which are associated with the crash environment. These modeling procedures are not totally free of reliance on testing, and good analytical engineering judgement must be used. The finite element computer programs suitable for crash simulation include WRECKER by Yeung, et al. (reference A-16), ACTION by Melosh, et al. (reference A-17), DYCAST by Pifko, et al. (reference A-18), and MSC/NASTRAN by MacNeal-Schwendler Corporation (reference A-19).

Reference A-2 presents the results produced by three programs, KRASH, ACTION, and DYCAST, used to analyze the dynamic response of a twin-engine, low-wing airplane section subjected to a 27.5-ft/sec vertical impact velocity crash condition. The report contains brief descriptions of the three computer programs, the respective aircraft section mathematical models, pertinent data from the test performed at NASA Langley, and a comparison of analysis versus test results. Cost and accuracy comparisons among the three analyses are presented to illustrate the possible uses of each of the programs.

The remainder of this section discusses the computer programs of greatest potential use in aircraft structural crashworthiness.

A.1.2.1 Program KRASH. The computer program KRASH was originally developed by Lockheed-California Company under U.S. Army support, to analyze the dynamic response of helicopters subjected to a multidirectional crash environment. Subsequent development of KRASH was sponsored by the Federal Aviation Administration (FAA). The general aviation version of KRASH has been exercised on four full-scale, single-engine, high-wing, aircraft crash tests performed at NASA Langley Research Center's Impact Dynamics Research Facility.

Program KRASH is a hybrid structural crash simulation program. It utilizes nonlinear spring and beam elements and rigid body masses arranged in a three-dimensional framework to simulate the fuselage structure. The nonlinear characteristics needed to describe the structural elements are derived from tests or other analyses and input to KRASH.

A summary of the features of the KRASH program important to the engineering user are the following:

- Lumped-mass representation for aircraft structure and occupants.

- Nonlinear external spring elements used to model nonlinear crushable structure, landing gear, soil, friction, and plowing reactions.

- Nonlinear beam elements to model airframe structure. Nonlinear properties are defined via stiffness reduction fractions (KR). Structure failure can be modeled by specifying forces or displacements at failure.

- Initial conditions of linear and angular velocity about three axes and impact into a horizontal ground and/or inclined slope.

- Symmetric and unsymmetric impact conditions.

- Large structural displacements and rotations. Rigid elements via massless nodes.

- Mathematical model analysis containing up to 80 masses and 150 internal beam elements, with up to 180 nonlinear degrees of freedom.

Output parameters available from program KRASH are as follows:

- Mass point response time histories (displacement, velocity, acceleration).

- Distribution of kinetic and potential energy by mass item, distribution of strain and damping energy by beam element, and crushing and sliding friction energy associated with each external spring.

- Occupant survival indicators: livable volume change, mass penetration into an occupiable volume, probability of injury indicated by Dynamic Response Index (DRI).

- Overall vehicle c.g. translational velocity.

- Energy distribution by mass, beam, and spring elements.

A comprehensive discussion of the theoretical development, input-output techniques, and modeling guidelines can be found in references A-20 through A-22. Information related to the program's system requirements is contained in reference A-23.

Examples of helicopter structure models analyzed by KRASH are the existing utility model shown in figure A-1 and medium cargo model shown in figure A-2 (reference A-24). Also, demonstrating the use of KRASH to model a structure in greater detail, figure A-3(a) illustrates a half-model of the cargo helicopter nose section, where symmetry is utilized in modeling the structure to the left of the aircraft mid-plane. Reference A-25 describes the drop test of the nose section of the cargo helicopter at an impact velocity of 33.3 ft/sec, as shown in figure A-3(b), and the correlation of test data with KRASH predictions. Other applications of program KRASH include analysis of crashworthy floor design concepts (reference A-26) and analysis of helicopter fuselage structures constructed of composite materials (reference A-27).

A.1.2.2 Program DYCAST. The computer program DYCAST (Dynamic Crash Analysis of Structures) is one module of the PLANS (Plastic and Large deflection Analysis of Structure) system of nonlinear finite element structural analysis computer codes. These programs have been developed under contract to NASA Langley Research Center as part of a joint NASA/FAA program in general aviation crashworthiness. The PLANS system of programs is described in reference A-1.

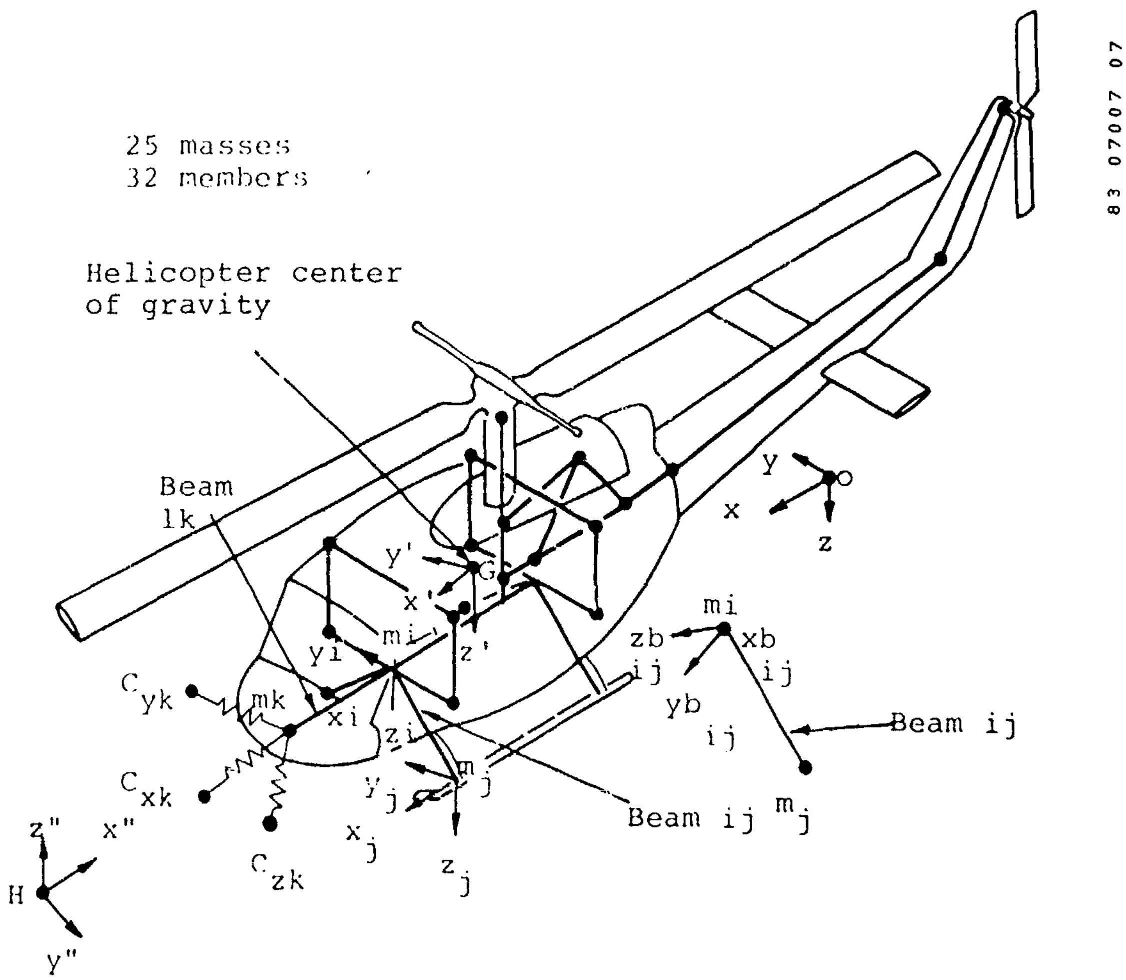


Figure A-1. Model of existing utility helicopter
(from reference A-12).

The major DYCAST features of importance to the engineering user are the following:

- Plasticity, where three types of stress-strain curves are permitted: elastic-perfectly plastic, elastic-linearly hardening, and elastic-nonlinearly hardening. Material property types provided for include isotropic plane stress, orthotropic with ideal plasticity, and orthotropic with orthotropic strain hardening.

- Element library that includes stringers, beams, membranes, plates, and springs.

- Very large displacements and rotations.

- Four different numerical solution methods, three with internally-varied time steps.

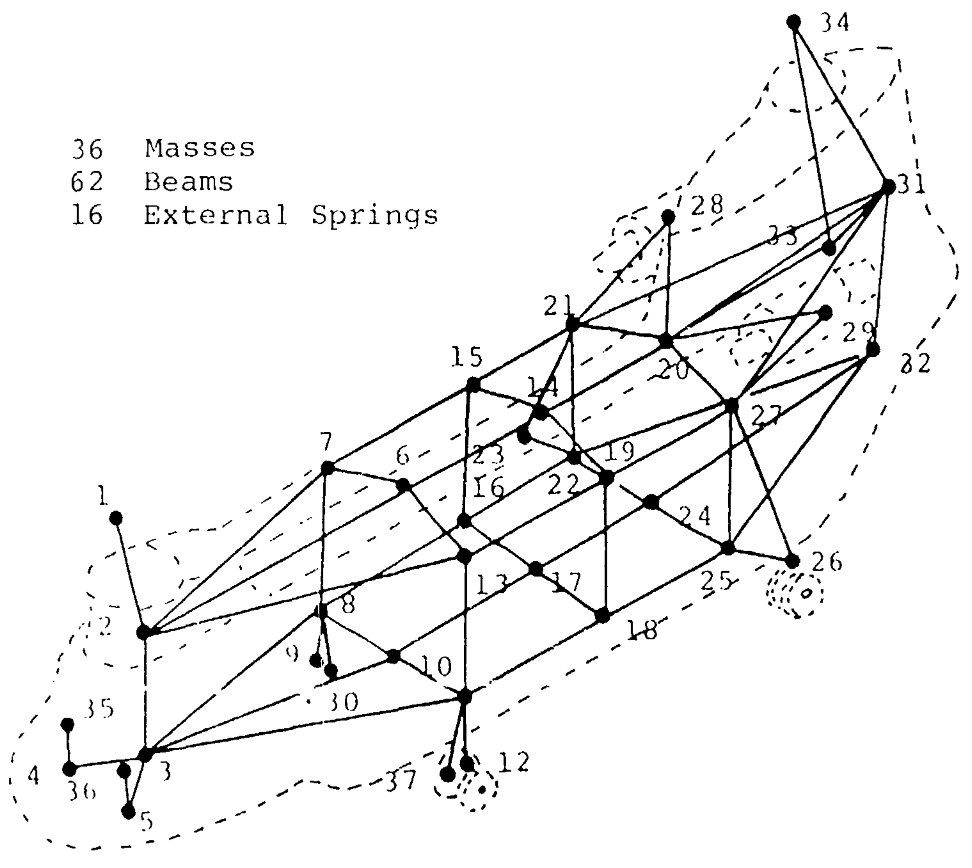
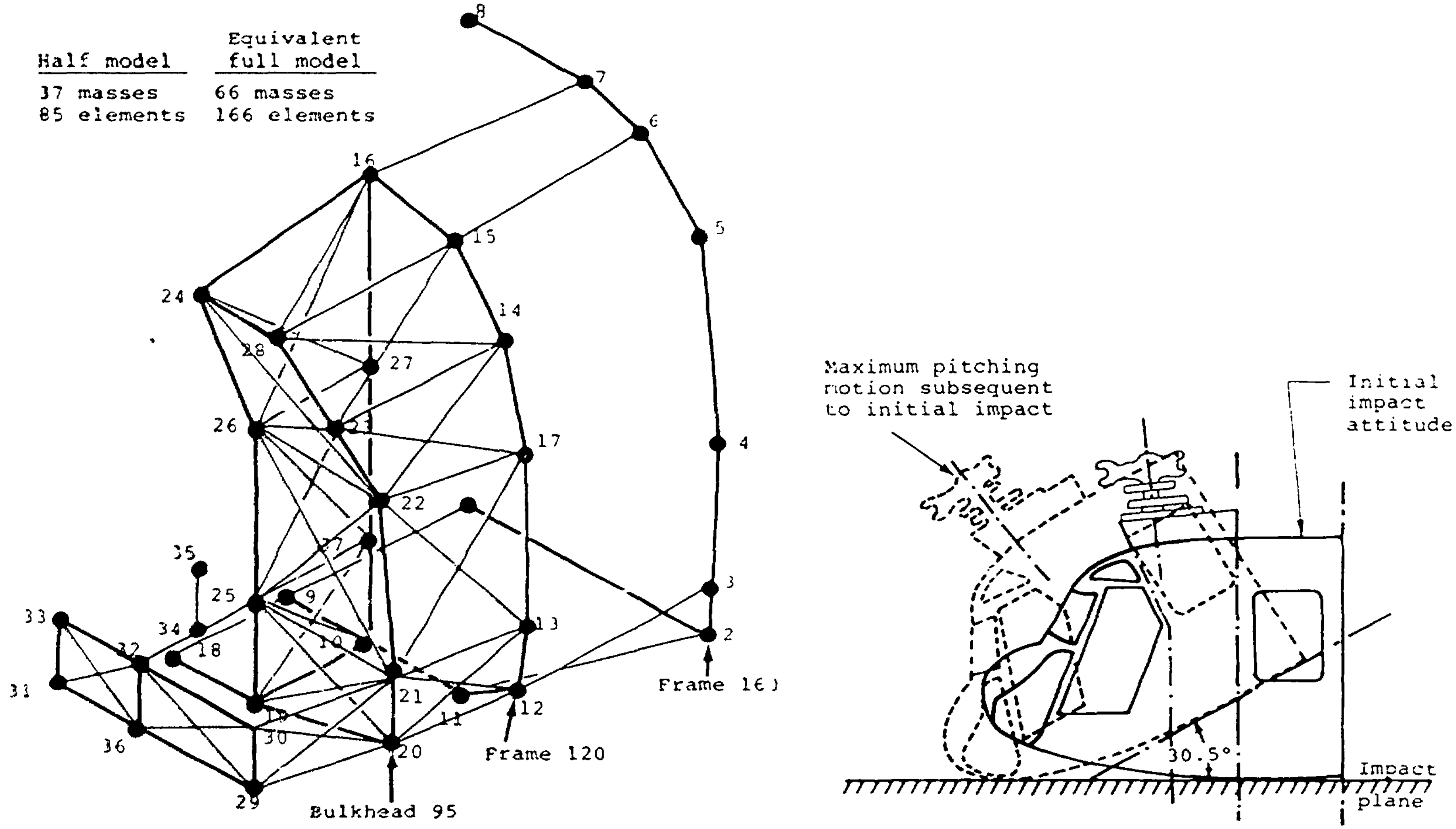


Figure A-2. Model of existing medium cargo helicopter (from reference A-24).

- Detection of failed members.
- Restart capability.
- User-oriented input/output format.

DYCAST accounts for two types of nonlinearities which occur in dynamically loaded structures: material and geometric. The nonlinear material behavior, exhibited by metals yielding plastically, is accounted for in the simulation through the stress-strain curves in the input data. The element stiffness during the simulation is determined using the tangent moduli corresponding to the current stress and strain, generalized for multiaxial states at various points on the element cross section.

Geometric nonlinearities due to large deformations of the structure change the effective stiffness of the structure and are treated in DYCAST by an incremental convected coordinate approach. After each time increment, the structure is reformed with straight elements between the displaced nodes; the previous values of accumulated strain, stress, and internal loads are carried forward as initial states in the reformed elements.



(a) Half model of existing medium cargo helicopter nose section

(b) Initial impact attitude and subsequent nose-down pitching motion in medium cargo helicopter nose section drop test

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Figure A-3. Simulation of CH-47 nose section drop test (from reference A-25).

Currently, both explicit and implicit algorithms are implemented in DYCAST. Central differences and modified Adams predictor-corrector methods are the explicit algorithms; and Newmark-Beta and Wilson- methods are the implicit algorithms. All methods but central differences permit a variable time step throughout the analysis.

The restart feature allows a large problem to be run in several parts. This minimizes the heavy demand on computer facilities and allows the user to examine the response as it progresses.

The output data include the following:

- Nodal displacements, velocities, and accelerations.
- Element strains and stresses through the cross sections.
- System energy distribution.
- Plots of time histories of displacements, velocities, and accelerations at user-specified nodes.
- Plots of the deformed structure at any time and from any viewing angle.

Further information on DYCAST is given in references A-18, A-28, and A-29. Reference A-2 presents a comparison of DYCAST and KRASH modeling of the same section of the fuselage structure. DYCAST analysis of helicopter fuselage structures constructed of composite materials is presented in reference A-27.

A.1.2.3 Program WRECKER. Program WRECKER has been developed by IIT Research Institute under the sponsorship of the National Highway Traffic Safety Administration for use in crashworthiness analysis of automotive structures.

The major WRECKER features of importance to the engineering user are the following:

- Static and dynamic analysis capability, including geometric and material nonlinearity with strain-rate effects.
- Plate, spring, and beam elements with optional force and moment releases.
- Both explicit and implicit solution procedures (fixed time step only).
- Restart capability (explicit solution procedure only).
- A capacity of approximately 150 nodes, 150 elements, 100 displacment boundary conditions, and five different sets of material properties.

The original version of WRECKER, documented in reference A-30, utilizes only the explicit solution procedure; the current version WRECKER II, described in reference A-16, has both explicit and implicit solution procedures.

In the explicit solution procedure, internal loads at the nodes are calculated from direct integration of element stress fields without reference to element

or assembled-stiffness matrices. The primary advantage of this procedure is that the program can be accommodated in a relatively small amount of in-core memory. The explicit solution method, however, requires relatively small time steps (typically 1/1000th of that required by the implicit method) for convergent solutions.

The implicit meth: requires the formation of element tangent stiffness matrices, assembly of these matrices into a master stiffness matrix, and inversion of the master stiffness matrix at each time step. This method requires considerably more in-core computer memory and computations. However, the implicit method is capable of carrying out dynamic analysis at substantially greater time steps than required by the explicit method and permits simulation of quasi-static crush phenomena involving slowly varying loading and structural response.

The treatment of large displacements and rotations employs decomposition of the element displacement field into a rigid body rotation and translation associated with the local coordinate system moving with the element, and a remaining displacement field which describes the deformation of the element relative to the current position of the element axes. In this manner, extremely large rotations and deflections can be accommodated by the analysis with an accuracy depending on the size of the elements relative to the curvature of the structure.

The computer program currently uses simple elastic-plastic stress-strain laws: a uniaxial relation for beam and spring elements, and a biaxial strain hardening Von-Mises relation for plates. Element forces and bending moment for given strain fields are calculated by piecewise linear numerical integration of the stresses at selected points in the cross section. Options of explicit moment-curvature relationships and strain rate effects are also provided.

The output data from WRECKER include the following:

- Nodal displacements, velocities, and accelerations.
- Element strains and stresses through the cross sections.

The explicit version of WRECKER II was validated through a series of test problems involving beams, plates, and shells subjected to various types of loading. References A-16 and A-30 contain the results of automobile crash simulations and tests as well as comparison of explicit and implicit solutions.

A.1.2.4 Program MSC/NASTRAN. Program MSC/NASTRAN is a proprietary version of NASTRAN, the NASA-sponsored computer program for structural analysis by the finite element method. MSC/NASTRAN has been marketed by the MacNeal-Schwendler Corporation since 1972. The latest version of the program, Version 61, includes nonlinear analysis capabilities for static and transient dynamics problems (reference A-19). The nonlinear capabilities for static and transient analyses are provided as self-contained solution sequences SOL 66 and SOL 99, respectively. These developments have superceded the original MSC/NASTRAN provisions for "Differential Stiffness" or "Piecewise Linear" analyses, which are now considered obsolete.

The nonlinear static and transient dynamic analysis features of MSC/NASTRAN important to the engineering user are summarized below:

- Nonlinear material property options including plastic and nonlinear elastic types, work-hardening functions and rules (Isotropic, Kinematic, or combined) and yield functions (Von Mises, Tresca, Mohr-Coulomb, Drucker-Prager). Also included are factors for stress limits and work hardening modules.

- Very large displacements and rotations (small element distortions).

- Element library for material/geometric nonlinear analysis including rod, gap, beam, quadrilateral and triangular membrane/plate/shell, and hexa and penta solid elements.

- Newmark-Beta method for transient integration combined with the modified Newton's method for nonlinear solution iterations.

- Initial conditions not explicitly provided for user input in SOL 99. These must be generated by initial transient subcases or by restarts from a previous static solution.

- Static superelement logic provided with the restriction that all nonlinear effects are present in the residual superelement. The effects of the upstream superelements are reduced to linear stiffness matrices attached to the residual grid points.

- Restart capability.

- User-oriented input/output format.

In the nonlinear static analysis, SOL 66, the loading sequence for the structure is defined via the subcase logic in the Case Control Deck. The total load and boundary conditions are defined in each subcase with the subcase sequence following the actual physical loading sequence. Within each subcase the loads may be subdivided into equal increments, and, in addition, each load increment may require several iterations. User control over the load increments and iteration convergence is provided.

Nonlinear transient dynamic analysis, SOL 99, and nonlinear static analysis, SOL 66, share the same computer code and solution techniques and provide similar data storage and restart facilities. The transient solution is performed in a stepwise manner with time steps replacing load steps and with effects of mass and damping matrices added to the stiffness matrices. Solution methods used are Newmark-Beta method for transient integration and modified Newton's method for nonlinear iterations. The additional iteration steps provide equilibrium solutions at each time step, thereby guaranteeing stability and accuracy for arbitrary time step size.

The output data include the following:

- Nodal displacements, velocities, and accelerations.

- Element internal loads and stresses/strains.

- Plots of time histories of displacements, velocities, and accelerations at user-specified nodes.

- Plots of the deformed structure at user-selected times and viewing angles.

A.1.3 RECOMMENDED IMPROVEMENTS TO AVAILABLE PROGRAMS. The conclusions that can be drawn from this evaluation of computerized methods of analysis for crashworthiness applications are as follows:

- At present both advanced hybrid (KRASH) and nonlinear finite element (DYCAST, WRECKER, MSC/NASTRAN) programs are needed. The hybrid type of analysis is useful for preliminary design analysis, and for parametric studies for the entire airframe structure. The finite element program has the potential for detailed structural analysis using the engineering design data and may be used to develop input to the hybrid type of analysis.

- All of these programs can be improved for more user-friendly input/output and additional capabilities required for crashworthiness analysis work. Specific recommendations are included in the following sections.

A.1.3.1 Recommended Improvements to KRASH. The following improvements to program KRASH are recommended:

- Add descriptive names to identify input data types.

- Increase the number of massless nodes and beams.

- Allow arbitrary mass point numbering by user.

- Develop NASTRAN to KRASH input preprocessor.

- Develop a graphic postprocessor for deformed and undeformed model geometry plotting.

- Add a shear panel element to the element library.

- Provide a plastic hinge element for the internal structure modeling since the airframe structure often fails locally at a weak spot. A plastic hinge element can be formulated to allow for interactive failure modes.

- Increase the number of piecewise linear slopes for the load-deflection curves for external springs.

- Allow the user to apply arbitrary boundary conditions to model.

- Allow substructuring by inputing a 12 X 12 stiffness matrix.

- Employ a variable-time step integrator to reduce program execution costs. Also, an implicit integrator such as the Newmark-Beta method should improve numerical stability.

- Provide rigid body motion analysis option for impacts such as rollover where no significant structural response occurs for long periods of time. This would greatly reduce program execution costs.

- Implement an out-of-core equation solver to handle very large problems that cannot be solved in-core with the efficient sparse matrix techniques. Stiffness matrices could be blocked, and it would be necessary to allow only two of these blocks in-core at a time instead of the entire matrix. Using an out-of-core equation solver, very large problems could be solved with limited computer memory at the expense of increased input-output time.

- Allow arbitrary node and element numbering. This capability could be particularly useful during modification of the model when nodes and elements can be added or deleted with no renumbering.

- Present all output in neat tabular forms for displacements, element internal reactions and stresses, and constraint forces similar to those of existing general purpose finite element programs. The current output formats for displacements, forces, stresses, etc., are very cumbersome.

- Develop a graphic postprocessor for deformed and undeformed plots of the structural model, as well as for time history plots of displacements, velocities, and accelerations.

- Implement the capability to model open cross section beams in the plastic range. This is a very serious limitation of the current version of the program.

- Incorporate shear panel, membrane, and sandwich plate elements into the program. Shear panel and membrane elements do offer cost-effective alternatives to plate elements when used appropriately. Sandwich plate elements can be used to model some of the modern composite structures.

A.1.3.4 Recommended Improvements to MSC/NASTRAN. Recommended improvements to MSC/NASTRAN are as follows:

- The nonlinear analysis capabilities in MSC/NASTRAN, Version 61, have been developed for general purpose use. Therefore, some capabilities, like external crush springs, occupant survival indicators, and energy distribution data associated with programs developed specifically for crashworthiness, are not available. The possibility of incorporating these capabilities as special purpose modules to be invoked by rigid format alters (RFL) should be investigated.

- Beam element formulation for material nonlinearity involves at each end plastic hinges, which couple axial motion and rotations. Linear material behavior is assumed for the center section of the beam and also for transverse shear and torsion. This nonlinear beam formulation is inadequate for crashworthiness analysis. In the plastic range beam element stiffness matrix coefficients should be calculated by numerical integration over the beam cross section and over the length of the beam. To accomplish this several distinct beam cross section types used in aircraft structures (i.e., tubes, L-, T-, S-, I-sections, etc.) should be incorporated into the program.

A.1.4 <u>AIRFRAME MODELING USING KRASH AND DYCAST</u>. A section of DC-10 fuselage was modeled to evaluate and to illustrate the use of programs KRASH and DYCAST in a manner complementing each other by using the strong points of each of the programs. The DC-10 fuselage section was 10-ft long and was capable of accommodating seating for three rows of nine passengers for a total of 27 passengers. The section also contained six fuselage frames. The fuselage frame structure at Station 1039.00 is shown in figure A-4.

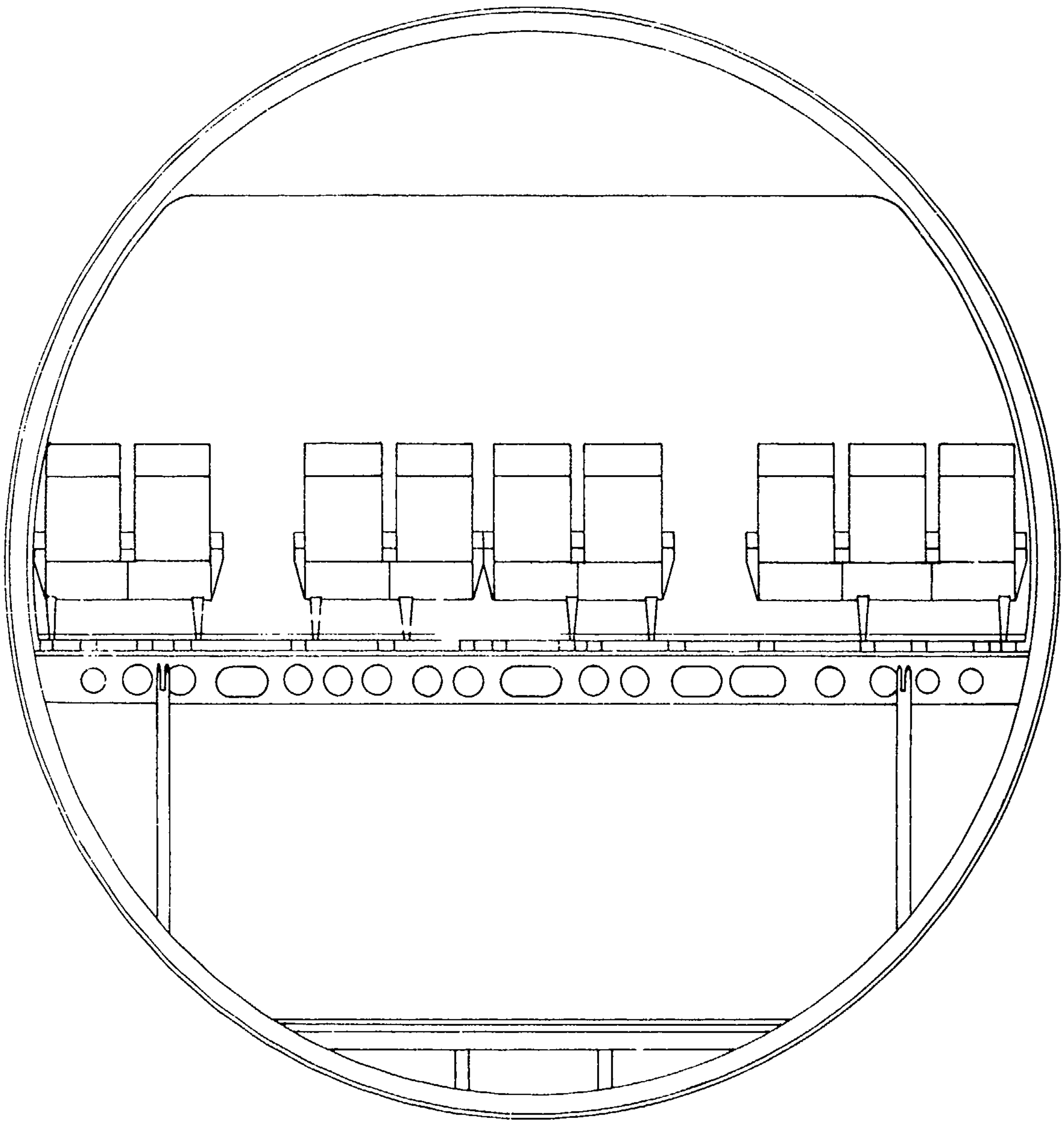


Figure A-4. DC-10 fuselage structure at station 1039.00 (looking aft).

Program KRASH was used to develop a two-dimensional model of the fuselage frame structure as shown in figure A-5. Due to non-symmetric location of the seats a full model of the structure was developed. The upper fuselage and passenger floor were modeled using beam elements. The lower fuselage was modeled by two nonlinear external springs simulating the force-deflection characteristics of the lower fuselage structure. The weight of the fuselage was 25 lb/in. The lower fuselage frame mass was lumped at nodes 10 and 11.

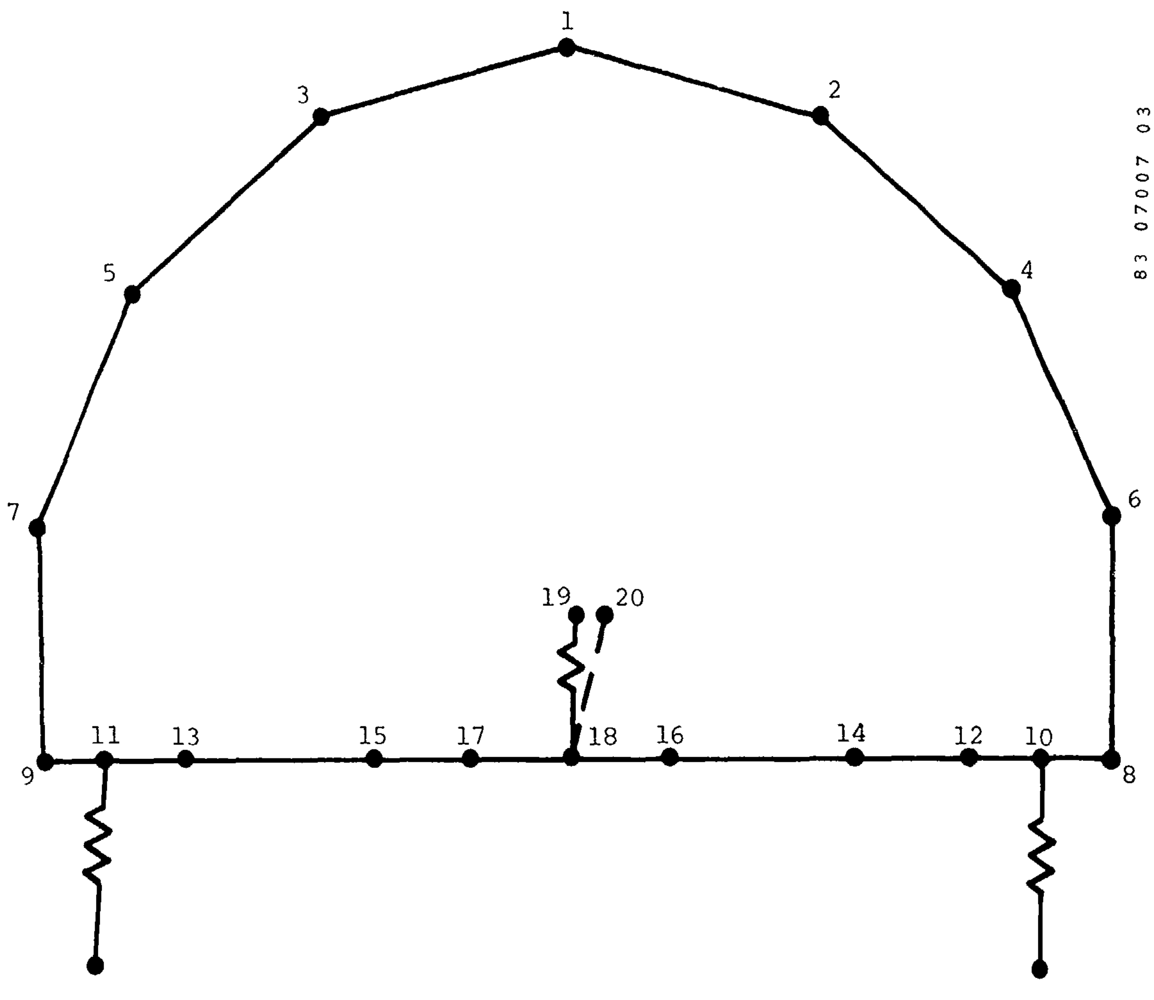


Figure A-5. Program KRASH model of the DC-10 fuselage at station 1039.00.

The masses for all nine passengers were included in the model but only one passenger is modeled in detail. The other passenger and seat masses are lumped at floor nodes 10 though 17. Masses 19 and 20 represent the upper torso of the center passenger. The lower torso and seat mass for this passenger were lumped at node 18. A DRI beam element is also connected between nodes 18 and 20. These beam element axial stiffnesses were selected to be 10 Hz and 8 Hz for the center passenger and DRI, respectively. The occupant weight and seat weight per occupant used were 170 lb and 25 lb, respectively.

Program DYCAST was used to model the lower fuselage frame in order to determine the nonlinear force-deflection characteristics of that area. The results from the DYCAST analysis were then incorporated into the KRASH analysis as external spring properties. The two-dimensional DYCAST model of the lower fuselage frame is shown in figure A-6. Due to the symmetry of that part of the fuselage, only the left half of the frame was modeled. In order to enforce the boundary conditions, nodes 9 and 10 were fully restrained. Nodes 1 and 4 were free to move in the vertical direction; all other translational and rotational degrees of freedom at these nodes were restrained.

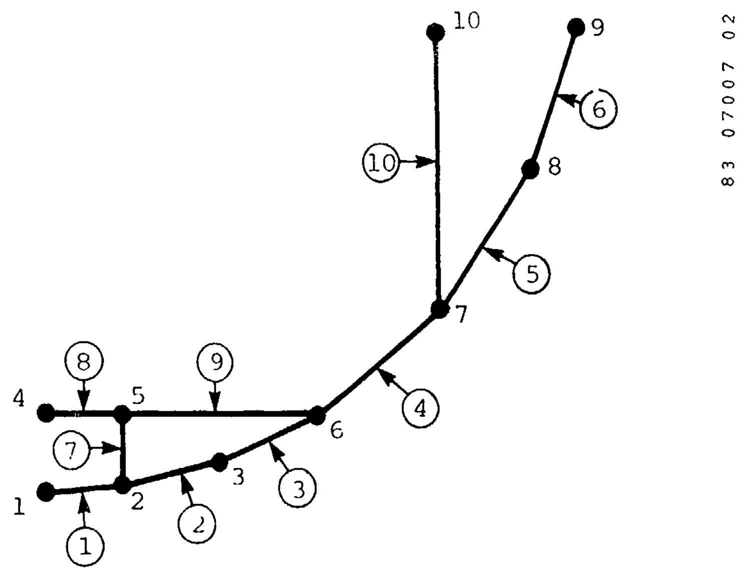


Figure A-6. Program DYCAST model of the DC-10 fuselage at station 1039.00.

The nonlinear force-deflection characteristics were determined from a static analysis, and specified displacements were applied at nodes 1 and 2 in an incremental manner. The implied applied forces were then determined from the reactions at nodes 9 and 10. This procedure utilizes the capabilities of DYCAST as an effective nonlinear finite element analysis program.

A.1.4.1 Results of KRASH and DYCAST Analysis. Program DYCAST was used to perform a static analysis to determine the nonlinear force-deflection characteristics of the lower fuselage frame. Specified displacements were applied at nodes 1 and 2 in increments of 0.10 in. Applied loads corresponding to the incremental displacements were then determined from the reactions at nodes 9 and 10. The nonlinear force-deflection curve of the lower fuselage frame obtained from DYCAST static analysis is shown in figure A-7. The beam element connected between nodes 6 and 7 failed after about 11.0 in. of deflection at nodes 1 and 2.

The results from the DYCAST analysis were incorporated into the KRASH analysis as external spring properties. Program KRASH was then used to perform a dynamic analysis of the fuselage frame and nine passengers. The impact velocity used

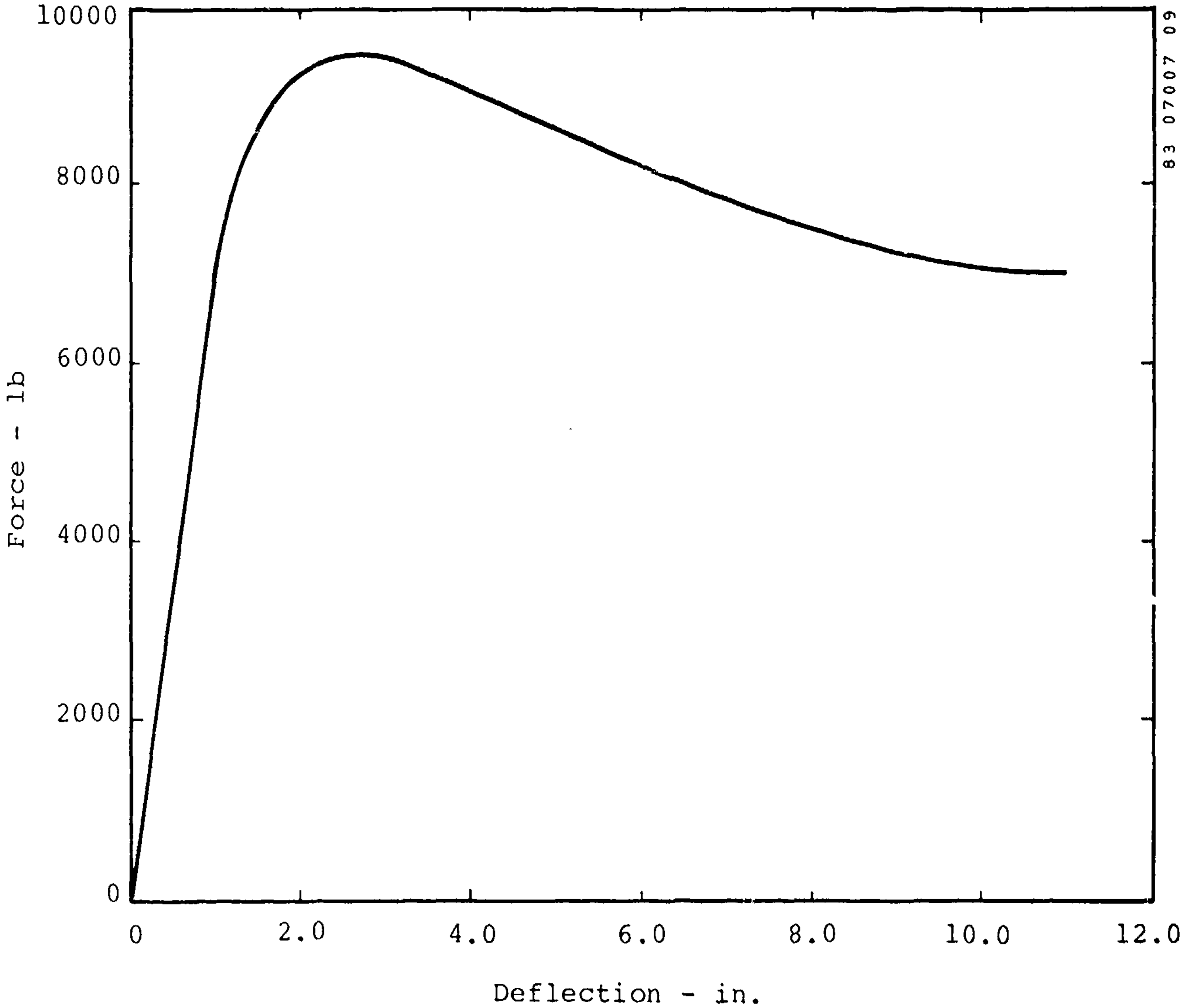


Figure A-7. Nonlinear force-deflection curve of the lower fuselage frame obtained from DYCAST static analysis.

was 20 ft/sec. An integration time step of 10^{-5} sec was used for the simulation. The total simulation time was 0.150 sec.

A useful KRASH output is the energy-versus-time curves shown in figure A-8. The energy distribution curves allow the engineer to readily determine how the energy is managed by the structure during the crash sequence, and to evaluate the roles of the crushable structure, strain in the internal structure, friction, and damping in absorbing the initial kinetic energy of the aircraft.

Another useful KRASH output is the center-of-gravity velocity-versus-time response of the aircraft shown in figure A-9. The center-of-gravity velocity represents on average velocity of all the masses during the crash sequence. This aids the engineer in determining the overall aircraft response during the crash sequence.

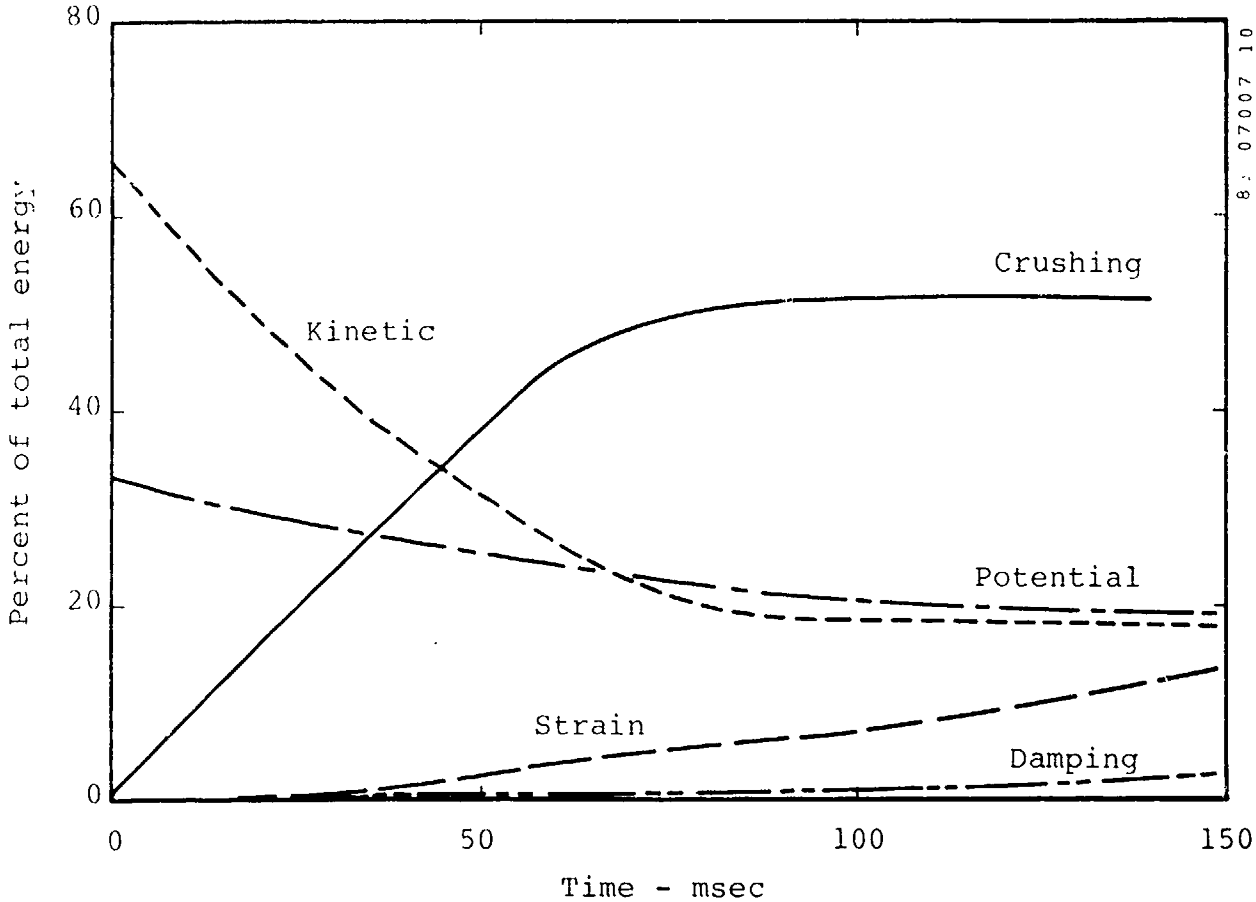


Figure A-8. Energy-versus-time curves from KRASH analysis.

Figures A-10 and A-11 show the vertical floor accelerations at node 18 and the DRI for the center passenger. Floor accelerations are filtered using a 100 Hz first-order filter. Although the validity of the DRI as an indicator of vertical spine compression injury is questionable, the DRI responds as a low-frequency, spring-mass system similar to the upper body vertical response to seat and floor excitation.

External spring compression-versus-time curves are shown in figure A-12. The left external spring had about 1.0 in. more deformation than the right external spring due to non-symmetric location of the passenger seats. Neither the upper fuselage nor the passenger floor suffered any permanent deformation.

It should be emphasized that the DC-10 fuselage frame was modeled primarily to evaluate and illustrate the use of programs KRASH and DYCAST in a manner complementing each other. Therefore, the results presented in this section should not be considered as the outcome of a rigorous analysis. A rigorous analysis of the 10-ft DC-10 section would require three-dimensional finite element modeling that includes beam and membrane elements to simulate the aircraft skin, as well as fuselage frame elements, accurate material and section properties, and local joint strength analysis, all beyond the scope of this effort.

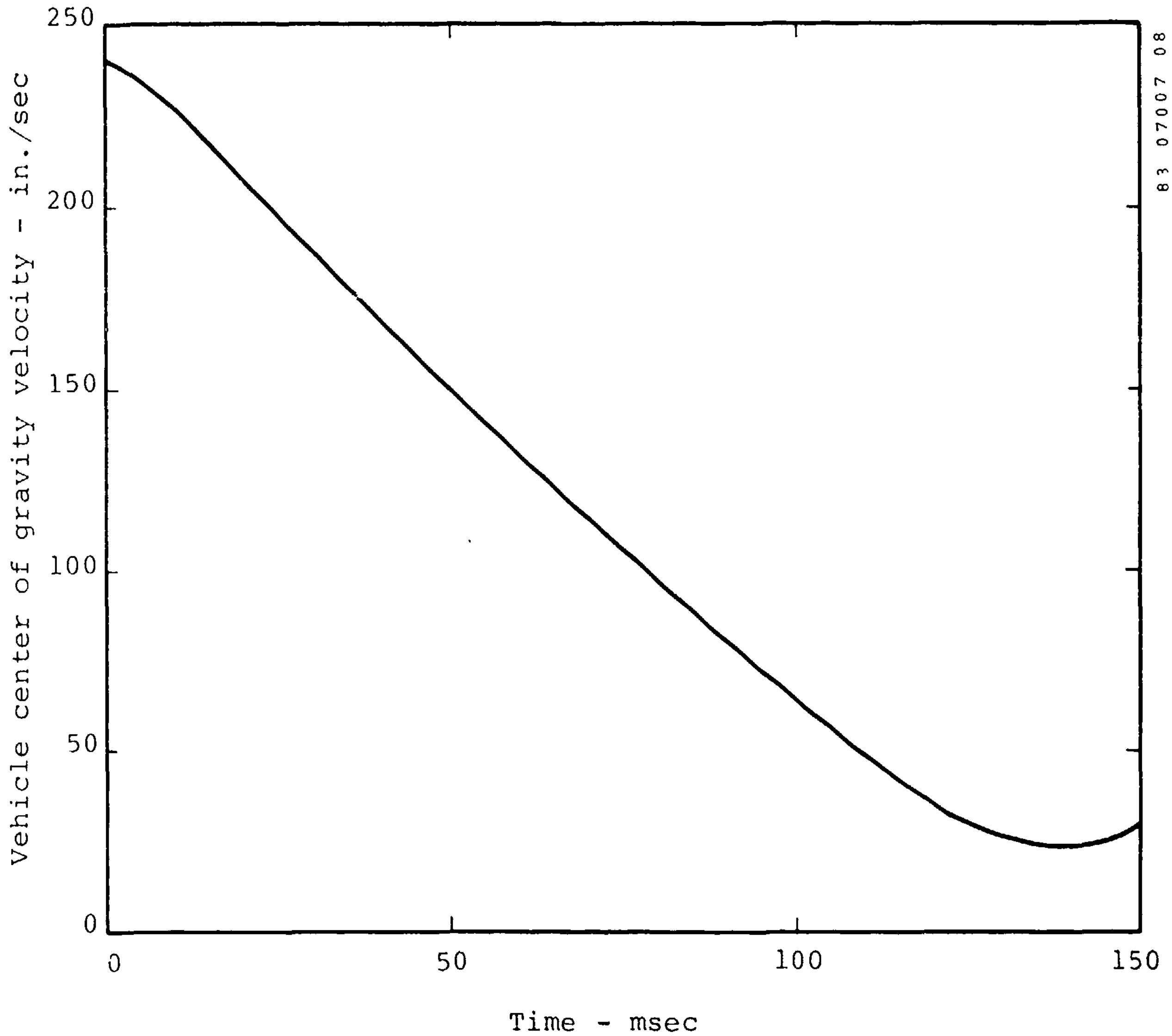


Figure A-9. Vehicle center of gravity-versus-time curve from KRASH analysis.

A.1.4.2 Resource Requirements. Both KRASH and DYCAST analyses were performed on a Digital VAX-11/750 computer. Representative CPU times for both analyses are presented in table A-1.

A.2 SEAT/OCCUPANT SIMULATION

The design of crashworthy seats and restraint systems for aircraft presents a complex engineering problem, the solution of which can be greatly aided by sufficiently rigorous analytical techniques. The crash environment can vary widely from one accident to another, thus a great number of conditions must be evaluated to establish those critical to occupant survival. For example, the restraint system must limit the movement of the occupant sufficiently to eliminate the possibility of head strike on rigid cockpit structure. Also, the

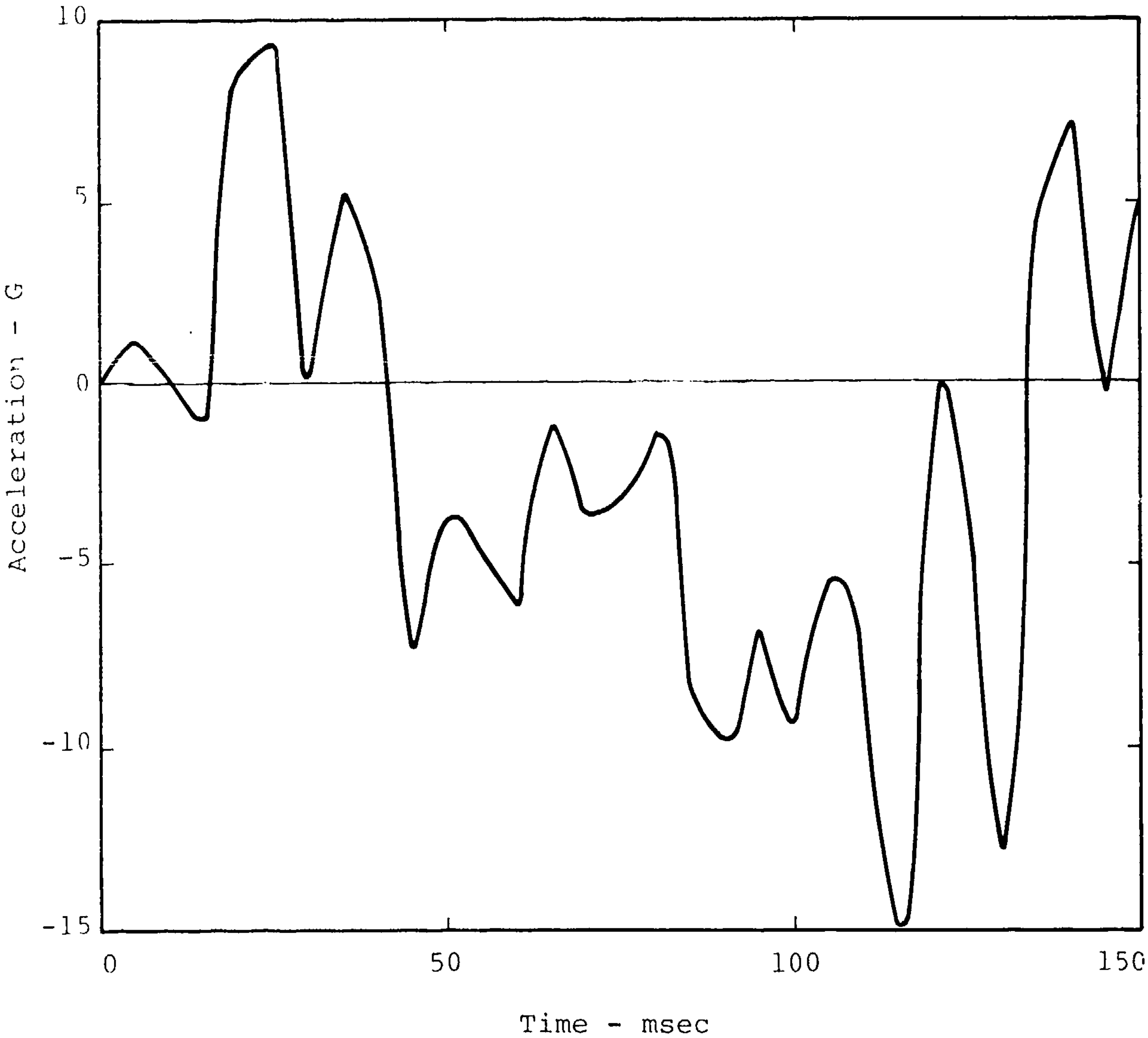


Figure A-10. Vertical acceleration at Node 18 (100 Hz low-pass filtered) from KRASH analysis.

relatively low tolerance of the human body to accelerations in a direction parallel to the spine requires the consideration of vertical impact forces which are usually present and often significant in crashes of light, fixed-wing aircraft and helicopters. A very strong, rigid seat is not a truly valid solution, since it would not only incur serious weight penalties, but would transmit high vertical impact forces directly to the occupant. In helicopters, it is usually not practical to consider designing sufficient energy-absorbing capability into the lower airframe structure to protect against these vertical forces, as the crush space is generally not available. Rather, a crashworthy seat for these aircraft should include the capacity to absorb energy through controlled deformation in the vertical direction, thus reducing the accompanying loads.

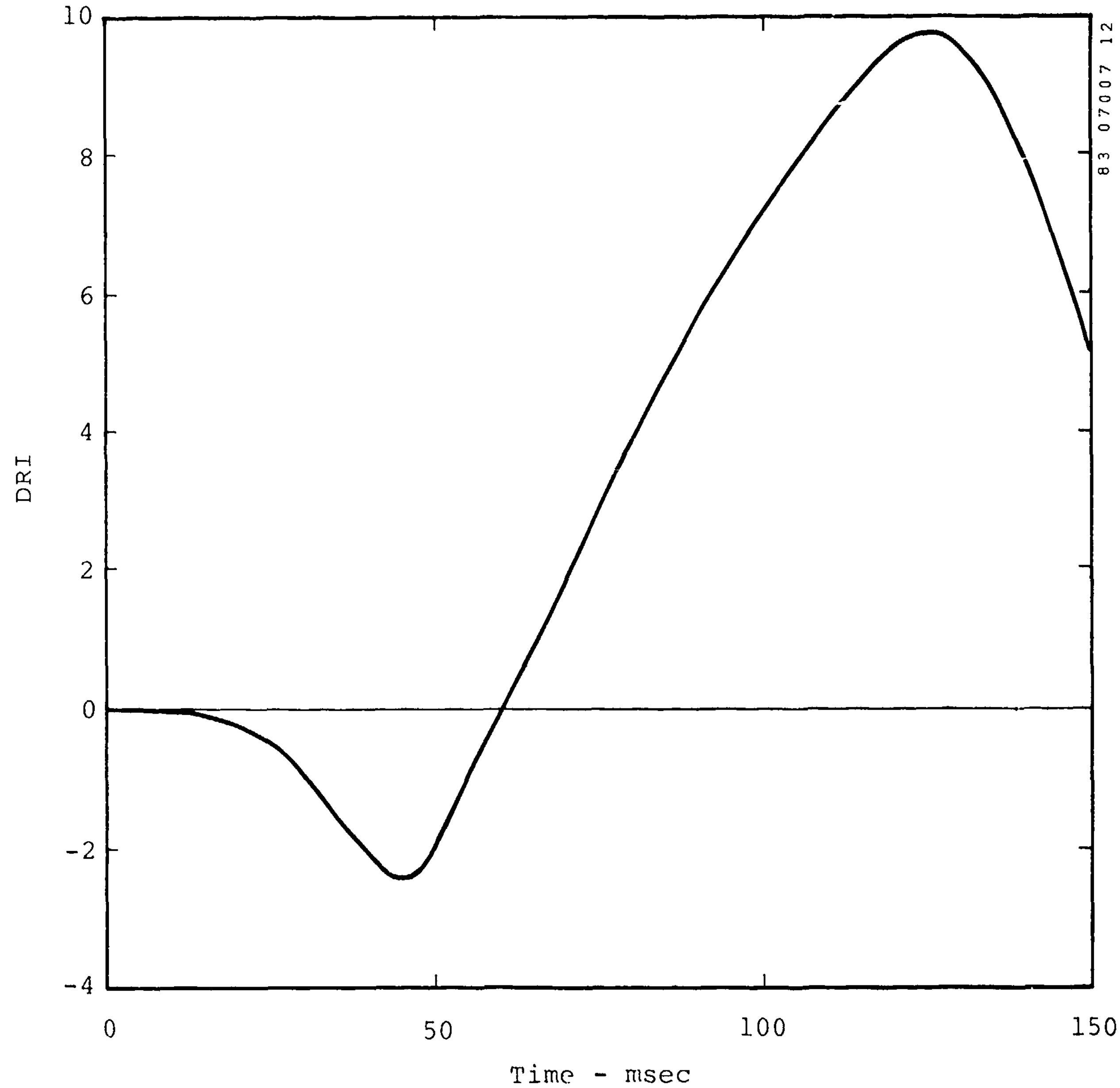


Figure A-11. DRI for the center passenger (node 20) from KRASH analysis.

In the initial design phases, it is desirable to evaluate, in some detail, existing seats and restraint systems in their surrounding cockpits, thus establishing existing weaknesses. It is then desirable to make modifications and to evaluate the effect of these modifications on improving the survivability of the system. These evaluations must be conducted for a great many of the possible crash environments, thus constituting a relatively large matrix. Testing is extremely expensive and requires a great deal of time, since design modifications must be developed and fabricated prior to testing. Therefore, an analytical technique is required.

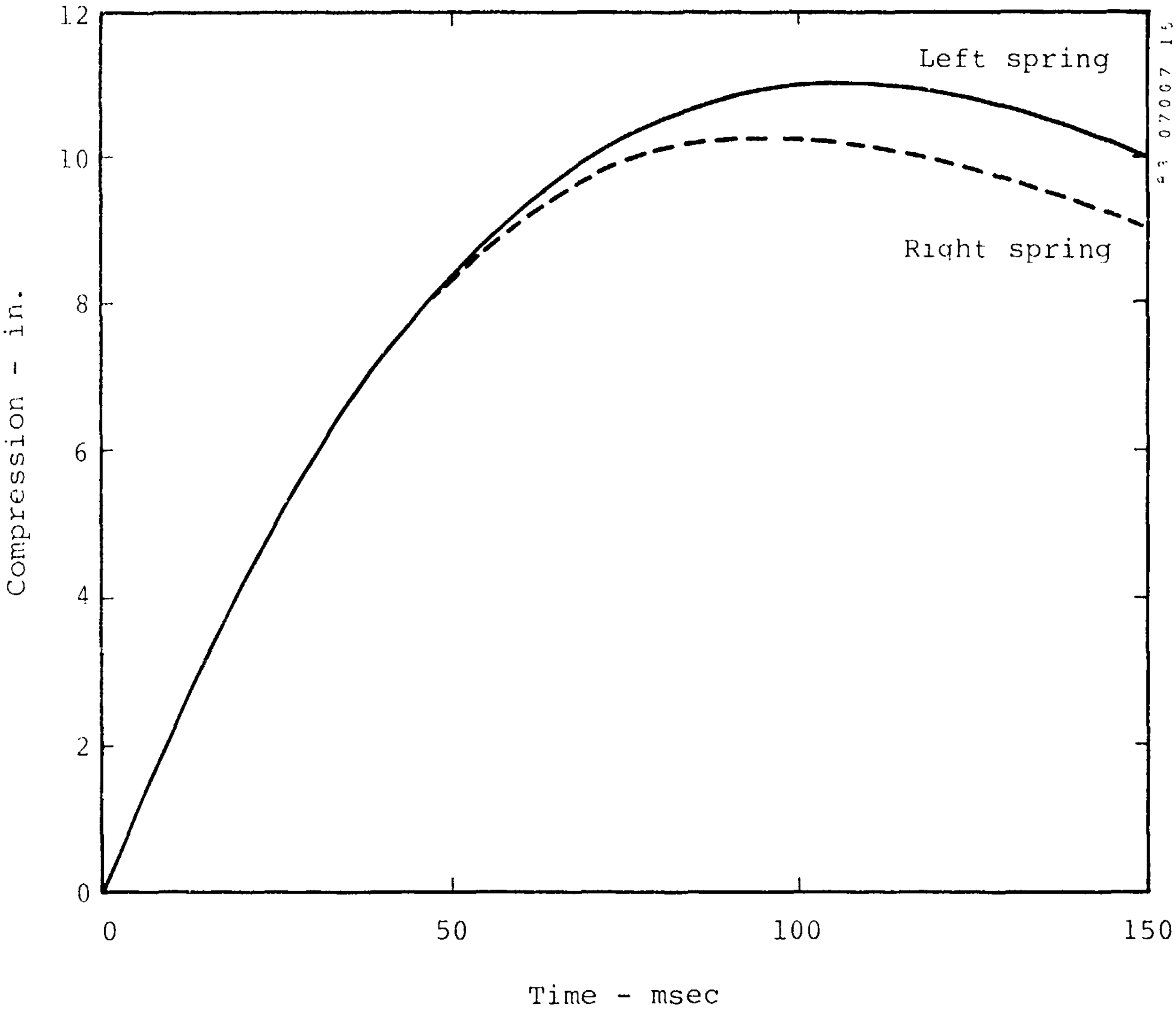


Figure A-12. External spring compression-versus-time curves from KRASH analysis.

A number of one-, two-, and three-dimensional mathematical models of the human body have been developed for crash survivability analysis. These models vary in complexity and possess from one to forty degrees of freedom. The simplest models have been developed primarily for prediction of injury to a single component or subsystem of the body. The Dynamic Response Index (DRI), calculated from the response of a single damped-spring-mass system, has correlated to the probability of spinal injury in the firing of an ejection seat (reference A-31). Two-dimensional occupant models have been developed and used by both automobile and aircraft manufacturers, as described in references A-32 and A-33, respectively. Simulation of the three-dimensional response of the entire body requires many more degrees of freedom, but permits more general use. Most of the three-dimensional models have been developed for use in evaluation of automobile interior design with respect to injuries caused by secondary impacts, such as the three-dimensional models described in references A-34 through A-37. Seats have been represented in a very simple manner because in automobiles the

TABLE A-1. DIGITAL VAX-11/750* CPU TIME FOR DYCAST AND KRASH ANALYSES

Analysis	CPU Time (Minutes)
DYCAST (Static Analysis)	
100 increments	6.02
2 iterations/increment (average)	
KRASH (Dynamic Analysis)	
$\Delta t = 10^{-5}$ sec	
t_{max} = 150 msec	100.32
Print interval ($tp/\Delta t$) = 500	

*Without floating point accelerator.

role of the seat design in determining occupant survival is minimal. Therefore, a simulation model intended specifically for aircraft application, including a rigorous seat model, is required for use in aircraft seat/restraint system design.

A.2.1 REQUIREMENTS FOR AIRCRAFT OCCUPANT/SEAT SIMULATION. The seat plays a significant role in the crashworthiness of light, fixed-wing aircraft and helicopters. Therefore, an analytical model that is to be useful in evaluation of occupant survivability must model the response of the seat in sufficient detail to permit evaluation of design changes. To be most useful to design engineers, the seat model should use only available dimensions and material properties, thus making a finite element approach most desirable.

For simulation of symmetric impacts, e.g., forward- or aft-facing seats with a symmetric restraint system in a zero-yaw environment, a two-dimensional model is adequate. However, for more general use a three-dimensional simulation capability is desirable.

For a model to be useful to engineers whose primary function is the design of seats, restraint systems, and the aircraft interior, an analytical tool should require as input only information that is available. Output data should include all information of potential utility concerning injury to the occupant and response of the seat, including stresses in the seat structure and displacements that reduce the clearance between the occupant and the cockpit surfaces.

A.2.2 AVAILABLE SEAT/OCCUPANT SIMULATION PROGRAMS. Two seat/occupant simulation programs are discussed in further detail below. Program SOM-LA (references A-38 and A-39) is the only program that includes sufficient detail in the seat model to be of general use. The PROMETHEUS II program (reference A-40) is included because it had been used in an aircraft seat evaluation program.

A.2.2.1 Program SOM-LA. The SOM-LA (Seat/Occupant Model - Light Aircraft) program, has been developed under the sponsorship of the Federal Aviation Administration for analysis of aircraft seats and restraint systems in a crash environment. The program combines a dynamic model of the human body with a finite element model of the seat structure. It is intended to provide the design engineer with a tool to analyze the structural elements of the seat as well as evaluate the dynamic response of the occupant during a crash.

The original model was described in a report that was published by the FAA in 1975 (reference A-41). A number of modifications have been made to the model since then to improve simulation quality and add desirable output. Several testing programs have been conducted by the FAA Civil Aeromedical Institute (CAMI) to provide data for validation of the mathematical model. The final model and its validation are described in reference A-38, with instructions for use of the computer program in reference A-39. These references describe the final phase of validation, which consisted of simulating dynamic tests of production general aviation seats. Capabilities of the program are described first, followed by a discussion of the actual simulations.

A.2.2.1.1 Occupant Model. Program SOM-LA includes a three-dimensional model of the human body, consisting of 12 rigid segments, as shown in figure A-13. The midtorso, lower neck, shoulder, and hip joints are ball-and-socket type, each possessing three rotational degrees of freedom. The upper neck, elbow, and knee joints are hinge-type joints, each adding one degree of freedom. In total, the occupant system possesses 29 degrees of freedom. Resistance at each of the body joints is modeled using both a nonlinear torsional spring and a viscous torsional damper. The relative contributions of each of these elements can be varied to simulate either a human occupant or an anthropomorphic dummy. In modeling motion of the human body, resistance of the joints is controlled mostly by viscous damping, whereas resistance in dummy joints is dominated by a constant frictional torque.

The external forces that act on the 12 body segments can be characterized as either contact forces or restraint forces. The contact forces applied to the occupant are those forces exerted by the cushions and floor, illustrated in figure A-14. They are calculated by first determining, from occupant displacement, the penetration of a rigid contact surface fixed to a body segment into either a cushion or the floor. Using the deformation, the force is then computed using an exponential model:

$$F = A(e^{b} - 1)$$

To each normal force, a damping term is applied which is proportional to the deflection rate. A variable damping coefficient is proportional to the instantaneous stiffness. Friction forces are also applied by the seat bottom cushion and the floor. Each friction force is directed opposite to the

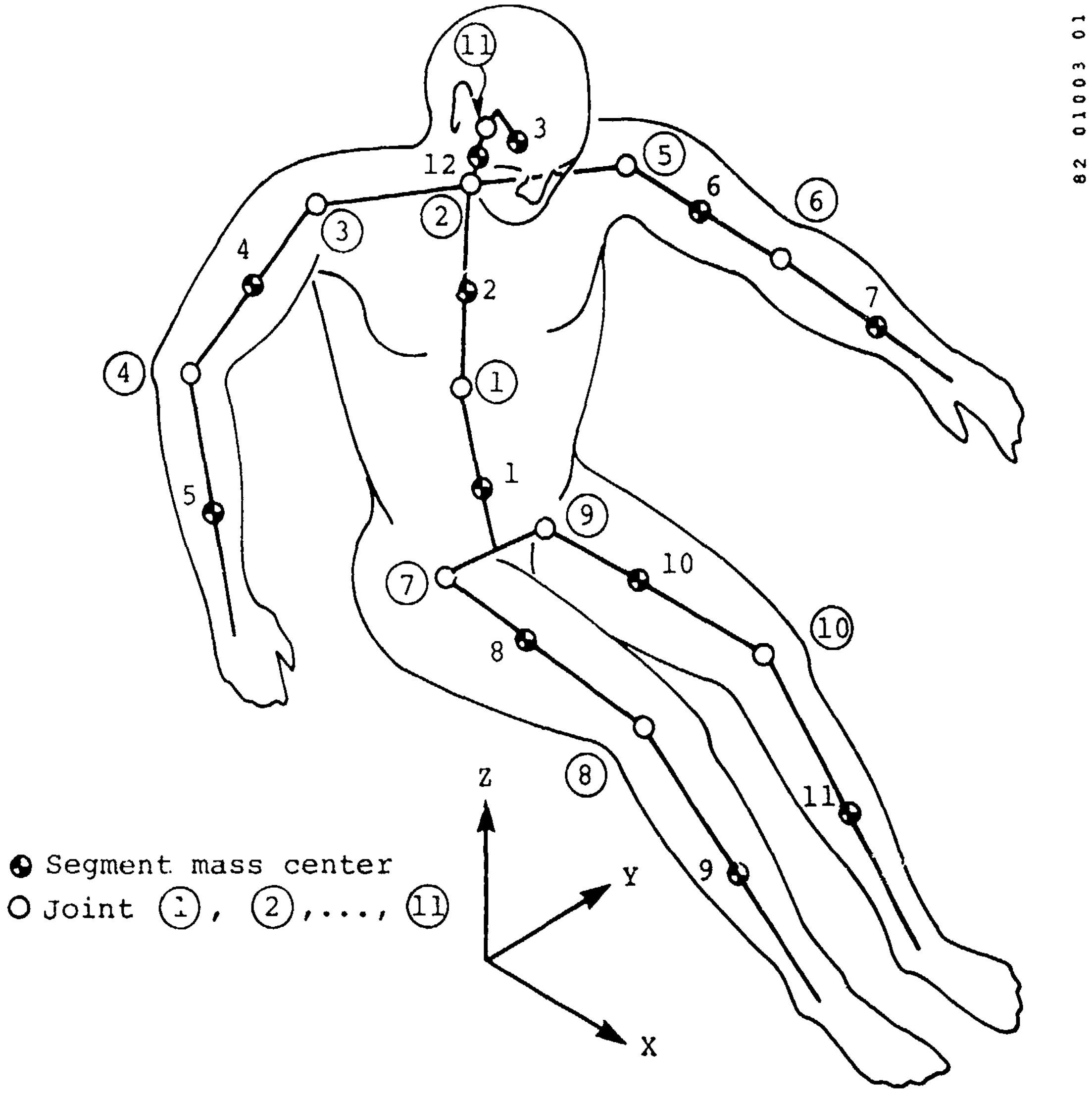


Figure A-13. Twelve-segment (three-dimensional) occupant model.

tangential component of relative velocity between the occupant segment and the appropriate cushion or floor surface.

The method used in calculating the forces exerted on the body by the restraint system differs considerably from that described above for the contact forces. The primary reason for this difference is that restraint forces do not act at any fixed point on the occupant, but rather, the points of application vary with the restraint system geometry.

Although other configurations can be selected by the user, a restraint system consisting of a lap belt and diagonal shoulder strap will be used as an example. The restraint loads are transmitted to the occupant model through ellipsoidal surfaces fixed to the upper and lower torso segments. These surfaces are shown in figure A-15. The locations of the anchor points A_1, A_2, and A_3 and the

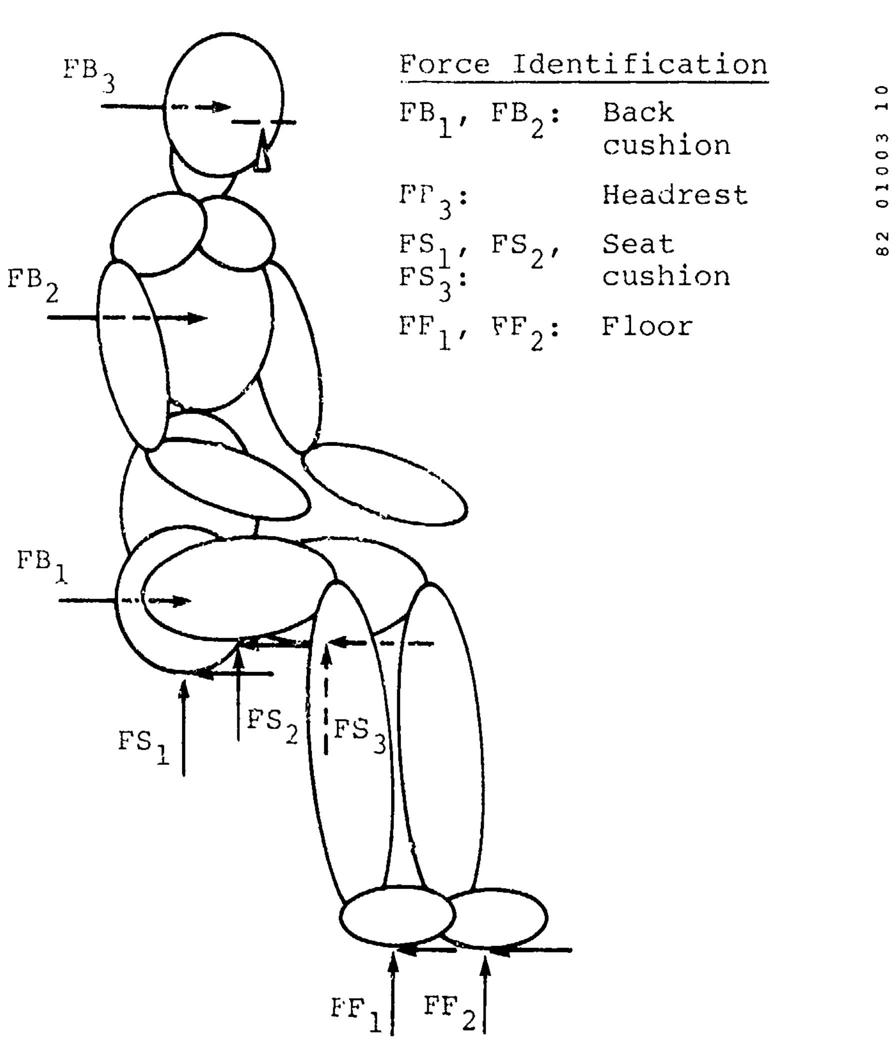


Figure A-14. External forces of cushions and floor.

webbing properties are determined by user input. The buckle B for a single shoulder belt is located according to an input parameter which specifies the distance from the appropriate anchor point, in this case A_1, along the path of the lap belt. For a double-strap shoulder harness, the buckle is placed on the abdominal contact surface between its intersections with the thigh surfaces.

The restraint forces are determined in the same manner for both the upper and lower torso. First, the belt loads are calculated from the displacements of the torso segments, and the resultant force on each segment is then applied at the point along the arc of contact between the belt and the ellipsoidal surface where the force is normal to the surface. Friction between the shoulder belt and the chest along the length of the belt is taken into account by reducing the load in the belt between the chest and buckle by a constant fraction of the load in the free length between the anchor point and the body surface.

The capability of the point of application of resultant belt loads to move relative to the torso surfaces allows simulation of submarining under the lap belt.

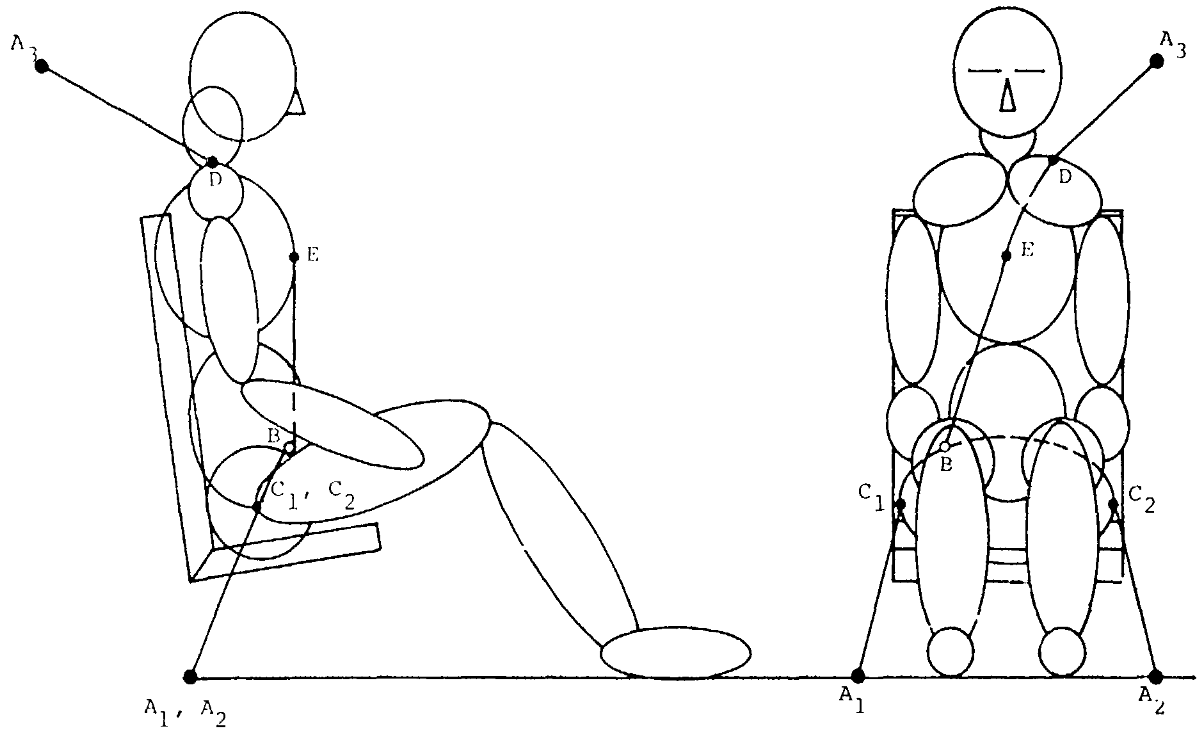


Figure A-15. Restraint system configuration parameters.

Characteristics required by the occupant model for each of the segments are the length, mass, center-of-mass-location, and mass moments of inertia. Also needed are the dimensions of body contact surfaces that are used for calculation of external forces exerted on the occupant by the seat cushions or restraint system and for prediction of impact between the occupant and the cockpit interior. For two standard occupants, a 50th-percentile human male and a 50th-percentile anthropomorphic dummy, all the required data are stored within the program. For other occupants, the above-listed data must be provided as input.

In order to achieve even more economical program solutions for cases where occupant response is expected to be symmetrical with respect to the X-Z plane, a second occupant model was included in SOM-LA. Although all forces applied to this model, such as those of the restraint system, are computed three dimensionally, its response is restricted to symmetric plane motion. All segments remain parallel to the X-Z plane, and both arms move identically, as do both legs. Because of the potential for vertebral injury in aircraft accidents that involve a significant vertical component of impact velocity, some measure of vertebral loading was considered desirable in the occupant model. The plane motion occupant model was configured to include beam elements in both the torso and neck, as shown in figure A-16, replacing joints that exist in the basic three-dimensional model. The plane motion model has eleven degrees of freedom, and the eight joints numbered in figure A-16 are hinge-type joints whose resistance is modeled as described above for the three-dimensional model. Axial and flexural stiffnesses of the two beam elements are represented by exponential functions, with a viscous damping term added.

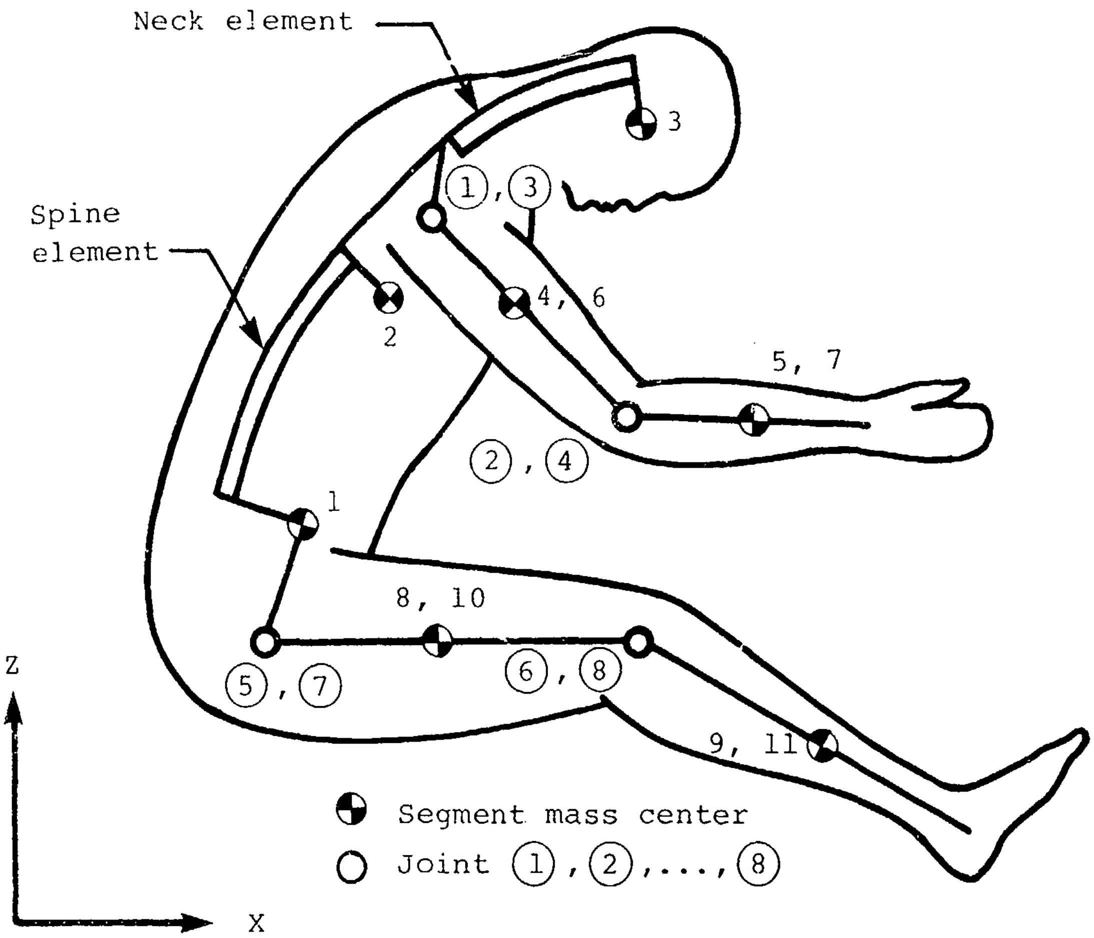


Figure A-16. Plane motion occupant model.

A.2.2.1.2 Seat Model. The seat structure is modeled using the finite element model of analysis, selected because it is not dependent on previous testing, and it has the flexibility to deal with a wide range of design concepts. The SOM-LA seat analysis includes triangular plate elements, three-dimensional beam elements, and spring elements. It has the capability to model large displacements, nonlinear material behavior, local buckling, and various internal releases for beam elements.

Nonlinear material formulation is based on a uniaxial elastic-plastic stress-strain law for beam and spring elements and a biaxial elastic-plastic stress-strain law (Von Mises yield criterion) for plate elements. Internal releases for beam elements include shear (transverse sliding joint), moment (transverse hinge joint), thrust (axial sliding joint), and torque (axial hinge joint) releases. Also, a simple local buckling model for thin-walled tubes subjected to axial compressive and/or bending loads was incorporated into the program. This model simulates the reduction in bending rigidity of the tube as the cross section distorts during local buckling.

A.2.2.1.3 Simulation Computer Program. The digital computer program based on the occupant and seat models described above has been written entirely in FORTRAN to ensure a high degree of compatibility with various digital computer systems. During development, the program has been run on IBM, Univac, CDC, and DEC computer systems.

Input data are read by the program in the following seven blocks:

1. Simulation and output control information.
2. Cushion properties.
3. Restraint system description.
4. Crash conditions.
5. Occupant description.
6. Seat design information.
7. Cockpit description.

Cushion load-deflection characteristics are described by an exponential function, whose coefficients are provided as input data. The equilibrium (zero load) thicknesses for both the seat and back cushions are entered, as is the cushion damping coefficient for zero deflection.

The restraint system used in the simulation may consist of the lap belt alone or combined with a single- or double-strap shoulder harness. A lap belt tiedown strap can also be included. The webbing force-elongation curve is approximated by three linear segments, which are described by input of points on the curve. The force is computed by linear interpolation in this table. The slack in the webbing is also provided by input in units of length. The anchor points for the lap belt, shoulder harness, and tiedown strap are located by input of rectangular coordinates in the aircraft reference system and may be fixed to either the aircraft or the seat.

The aircraft crash conditions are defined by the initial velocity and attitude and the acceleration as a function of time. Six components of velocity are required: three translational in the aircraft coordinate system and the yaw, pitch, and roll rates. Each of the six acceleration components, which define the motion of the aircraft coordinate system, is described by up to 16 points in time and acceleration.

The input data required to describe the seat consist of nodal coordinates, material properties, cross section geometries, element locations, and attachment conditions.

For prediction of impact between the occupant and the aircraft interior, ten planes are used to represent the cabin surfaces. During execution of the program, the distance between each of the occupant contact surfaces and the cabin surfaces is calculated. When contact occurs, the relative velocity of impact is computed and stored for output with surface identification.

The initial position of the aircraft occupant is computed for the input parameters shown in figure A-17. It is assumed that the occupant is seated symmetrically with respect to the aircraft (X_A - Z_A) plane or, equivalently, that the body segment y axes are all parallel to the Y_A axis. The angular coordinates γ_i (i = 1, 2, 3, 4) define the rotation of segments 1-4 relative to the Z_A axis, and, because of the symmetry conditions, segment 6 is parallel to segment 4. The angle γ_5 describes the position of the forearm's relative to the upper arms. The distance X_H is the initial X-coordinate of the heels. The initialization procedure consists of seating the occupant in such a position that static equilibrium is achieved among the forces exerted by the seat cushion, floor, and either the restraint system or the back cushion, depending on the aircraft attitude.

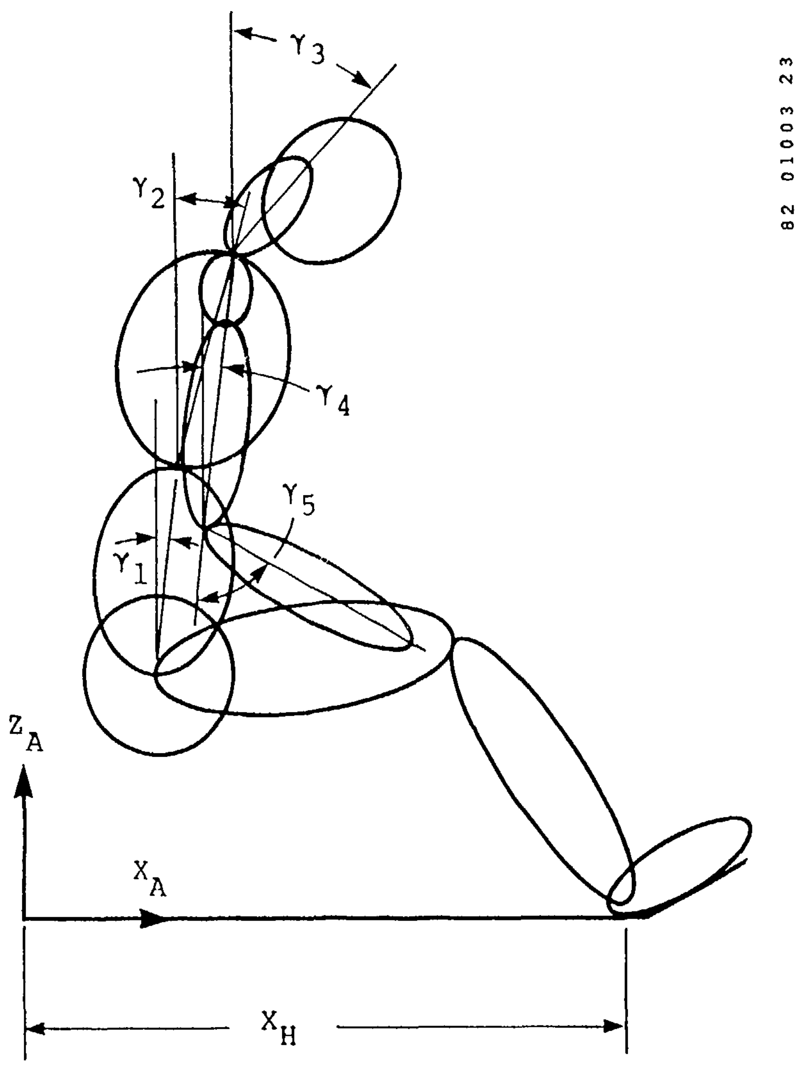


Figure A-17. Initial position input parameters.

Output data consist of ten blocks of information that are selected for printing by user input. The data include time histories of the following variables, which are stored during the solution at the predetermined print intervals:

1. Occupant segment positions in the aircraft coordinate system (X, Y, Z, pitch, and roll).

2. Occupant segment velocities in the aircraft coordinate system (X, Y, and Z).

3. Occupant segment accelerations in the segment-fixed coordinate systems (x, y, z, and resultants).

4. Restraint system loads.

5. Cushion loads.

6. Aircraft displacement, velocity, and acceleration.

7. Injury criteria (Severity Index, DRI, etc.)

8. Details of contact between the occupant and the aircraft interior.

9. Seat structure nodal forces.

10. Seat structure element stresses.

Printer plots are provided for occupant segment accelerations, restraint system loads, and cushion loads. The option of two different filters is provided for the occupant segment accelerations and cushion loads. Data are stored by the program for subsequent picture plots of occupant and seat position at user-selected times during the simulation.

A.2.2.1.4 Model Validation. SOM-LA validation has been based on data from several series of deceleration sled tests conducted at the FAA Civil Aeromedical Institute (CAMI). The response of the combined occupant and seat models has been verified by comparison with data from tests that utilized specially designed and fabricated seats that had replaceable legs. Test conditions were selected to cause significant plastic deformation of the legs. These test series are described in detail in reference A-42. Response of the occupant model, particularly to a vertical input acceleration, was validated using data from other test series that were conducted with a rigid seat and with a production energy-absorbing helicopter seat. The test configuration for some of the energy-absorbing helicopter seat tests is illustrated in figure A-18. For impact conditions of 42 ft/sec and the acceleration pulse shown in figure A-19, significant seat and dummy accelerations, seat stroke, and energy absorber load predicted by SOM-LA are compared with test data in figures A-20 through A-23.

Final validation used data from tests of production general aviation seats. One of the seats is shown prior to a test in figure A-24, and the finite element model of the seat structure, in figure A-25. The sled deceleration is shown in figure A-26. Significant dummy accelerations and belt forces are compared with test data in figures A-27 through A-31. The predicted progression of plastic deformation throughout the seat structure is illustrated in figure A-32, and occupant response, in figure A-33.

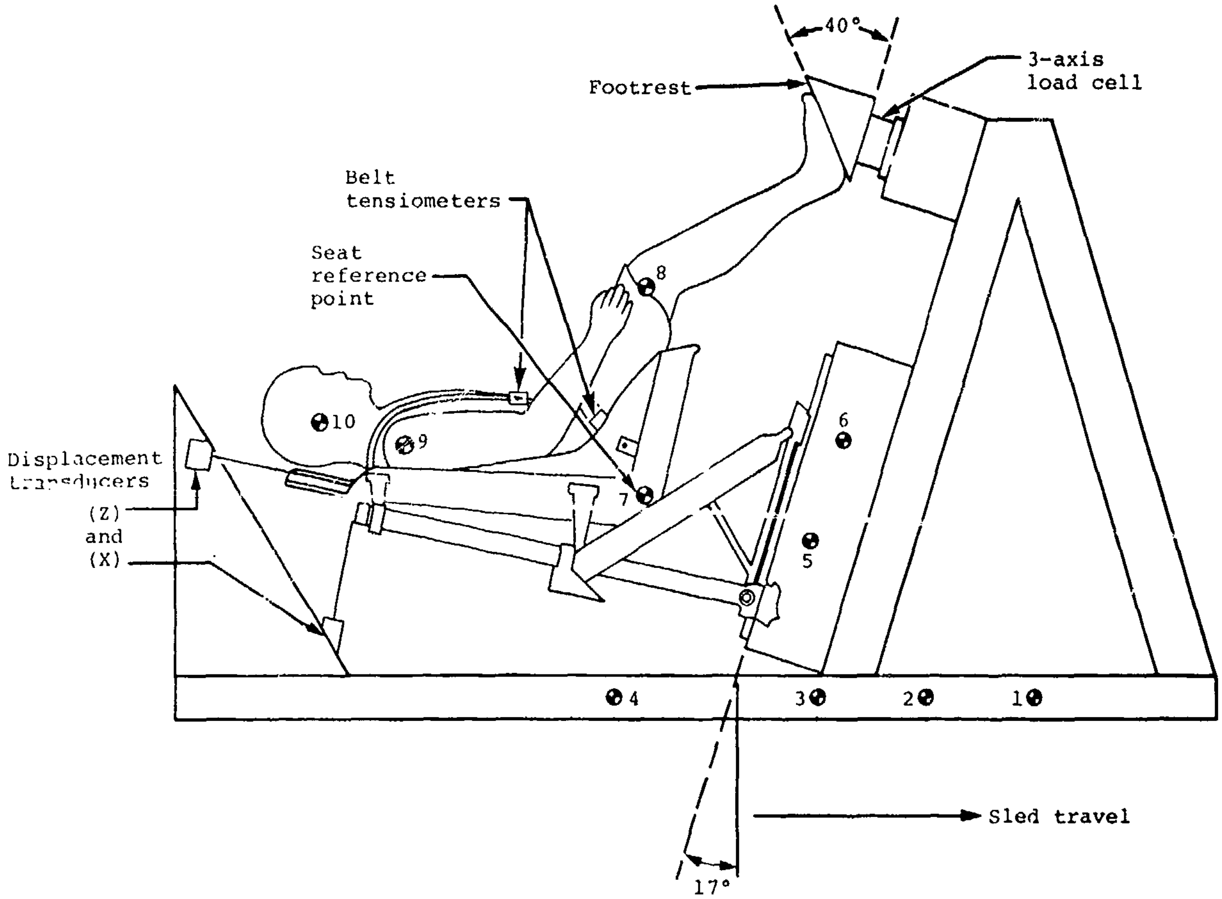


Figure A-18. Test configuration for CAMI tests with energy-absorbing helicopter seat.

A.2.2.1.5 Resource Requirements. CPU times for three simulations on two different computer systems are presented in table A-2. The energy-absorbing helicopter seat was modeled using the two-degree of freedom lumped-parameter seat option; the other two used the finite element seat model. All tests are described in reference 65.

A.2.2.2 Program PROMETHEUS. As described in reference A-33, PROMETHEUS was developed under Office of Naval Research support, starting with the existing Dynamic Science - Arizona State University program SIMULA. At this point PROMETHEUS was an interactive two-dimensional occupant model consisting of seven mass segments, as shown in figure A-34. Shoulder and hip nodes were connected to the seat structure by springs representing belts, and the seat was formed of springs and dashpots.

Under National Highway Traffic Safety Administration support, PROMETHEUS was refined to include two arms and two legs with distributed mass, and finite shoulder and hip widths, as shown in figure A-35. Modifications to the contact model were also made to permit simulation of the standing victim struck from the side by an automobile. PROMETHEUS II, described in reference A-40, approximates the vehicle surface with flat panels with specifiable orientations and stiffnesses.

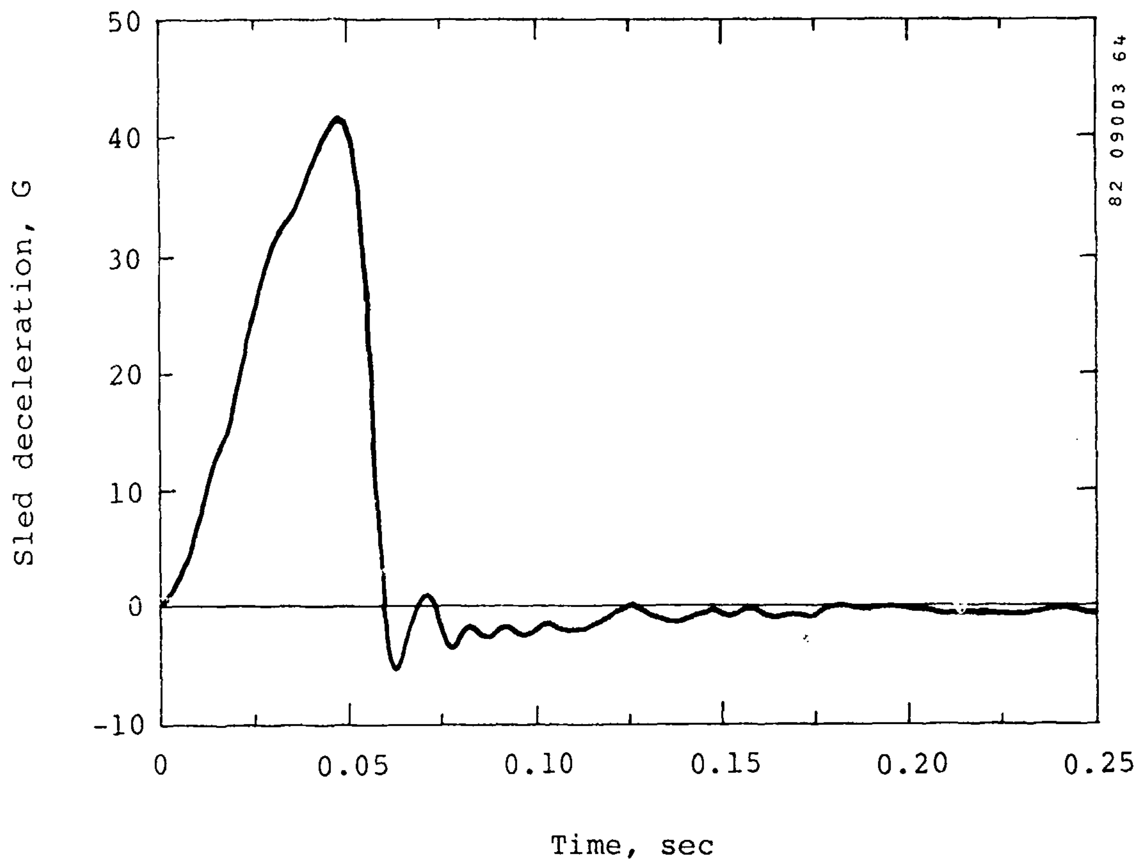


Figure A-19. Sled deceleration for energy-absorbing seat test.

PROMETHEUS III is a Boeing proprietary program that provides features different than its predecessors. In the earlier versions the articulation of the spine was limited, belt and harness were "pinned" to the joints, and anchors could not be moved to any possible position of choice. The latest version includes submarining, and added spinal joints and compression features more closely approximating the real spine. Figure A-36 notes some of the added features of PROMETHEUS III versus the earlier version.

PROMETHEUS III refinements (reference A-43) include the following:

Body Dimensions

Mass Distribution

Neck/Waist Stiffness

Muscle Tension

Joint Friction

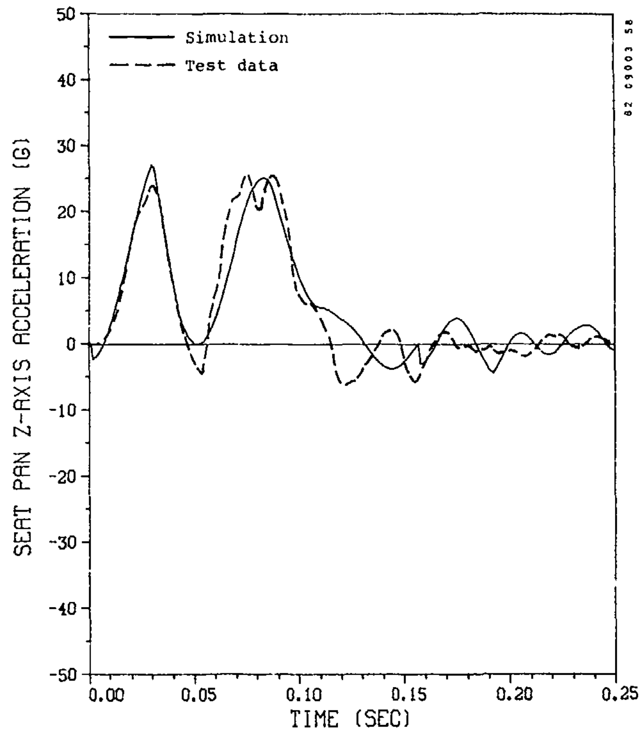


Figure A-20. Energy-absorbing helicopter seat test, seat z-acceleration.

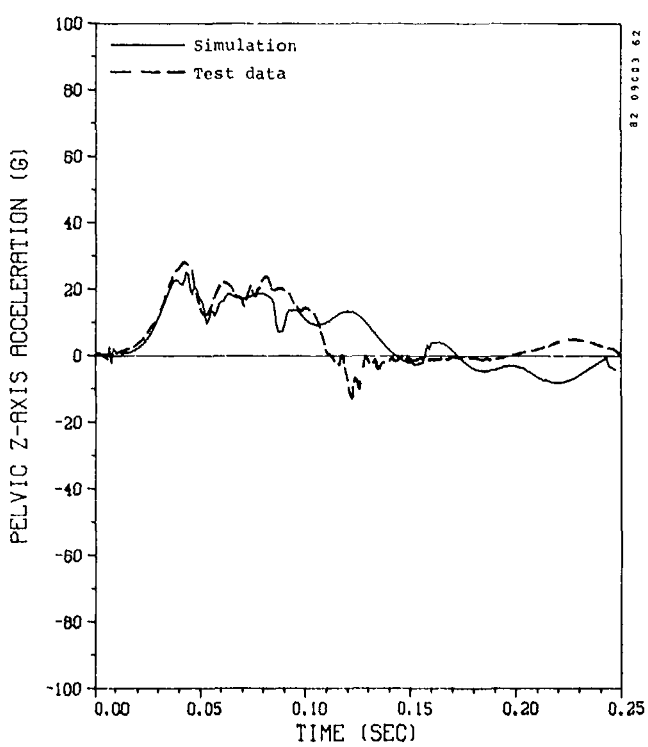


Figure A-21. Energy-absorbing helicopter seat test, dummy pelvis z-acceleration.

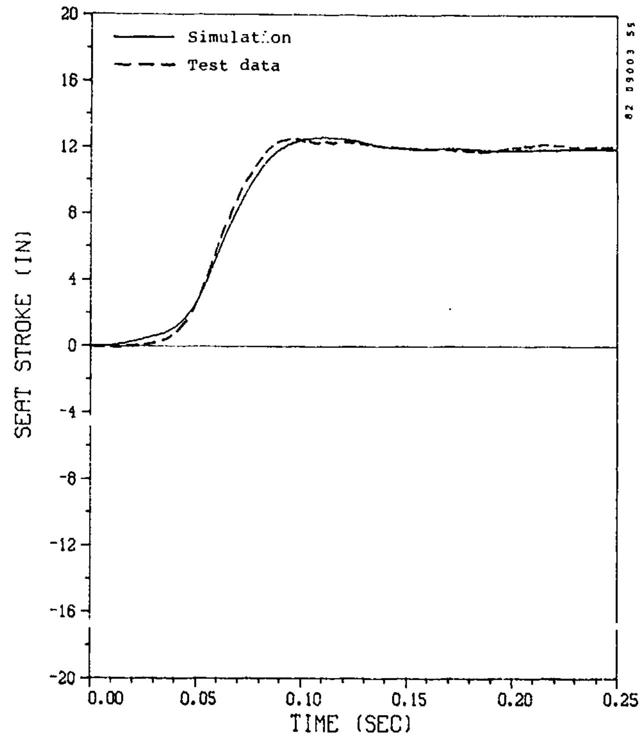


Figure A-22. Energy-absorbing helicopter seat test, seat vertical displacement.

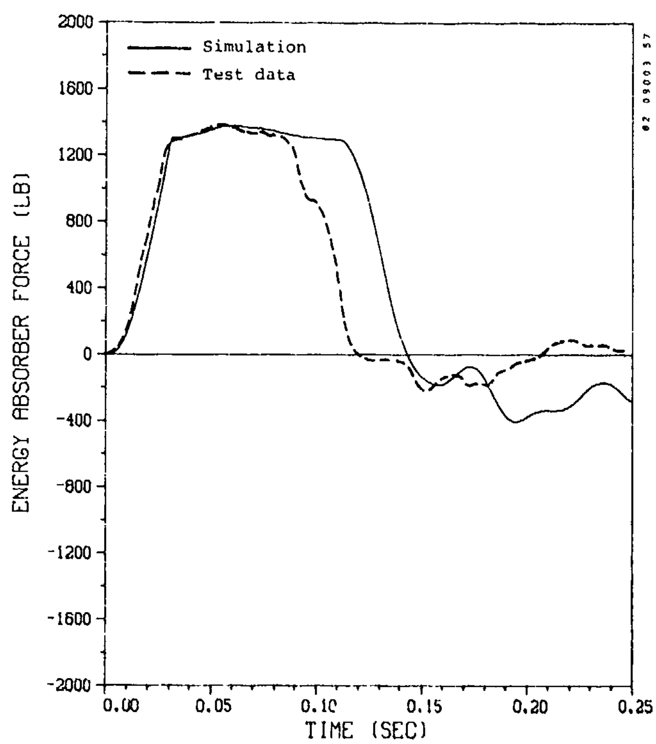


Figure A-23. Energy-absorbing helicopter seat test, energy absorber force.

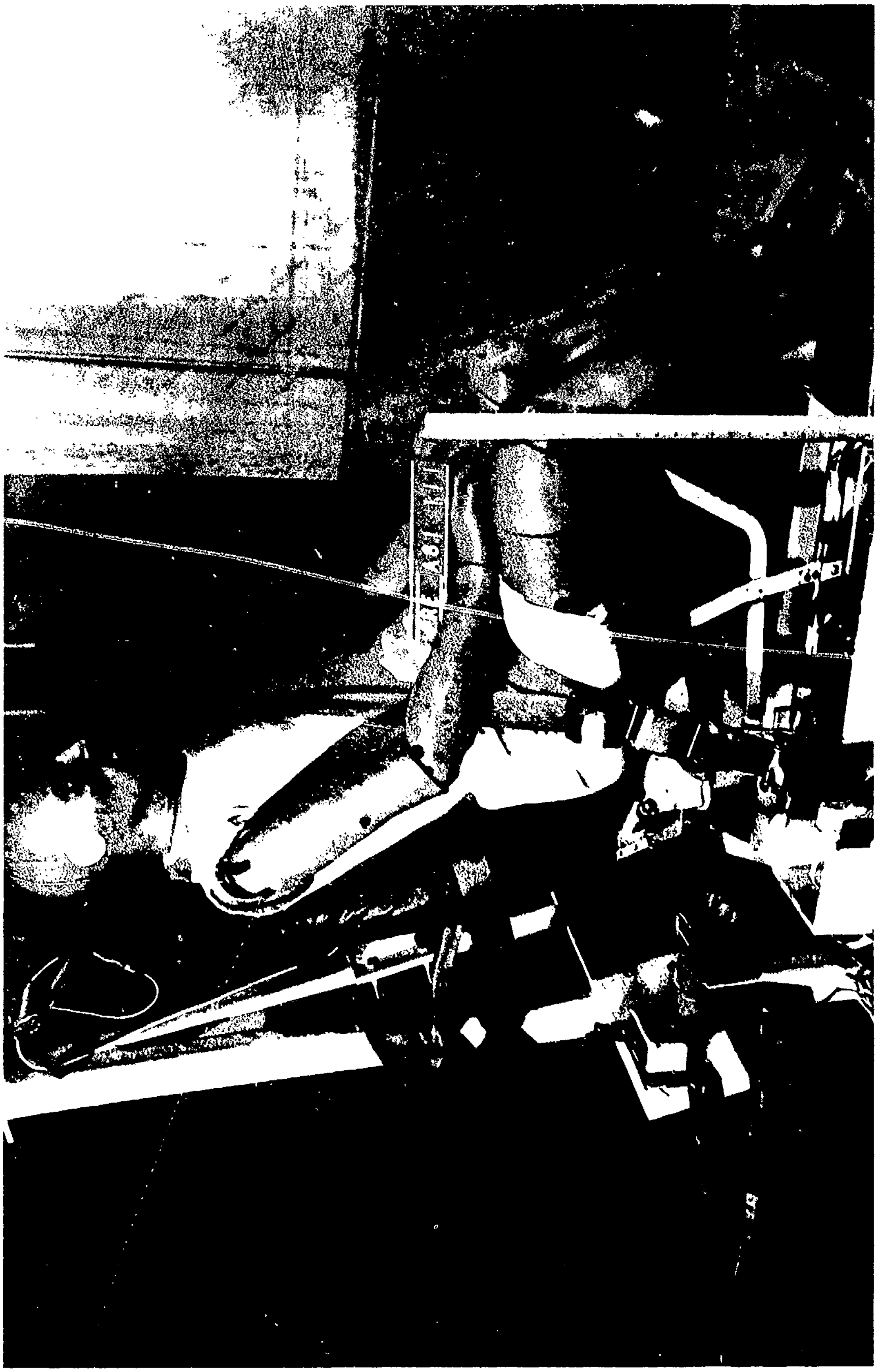


Figure A-24. General aviation seat and dummy prior to CAMI dynamic test.

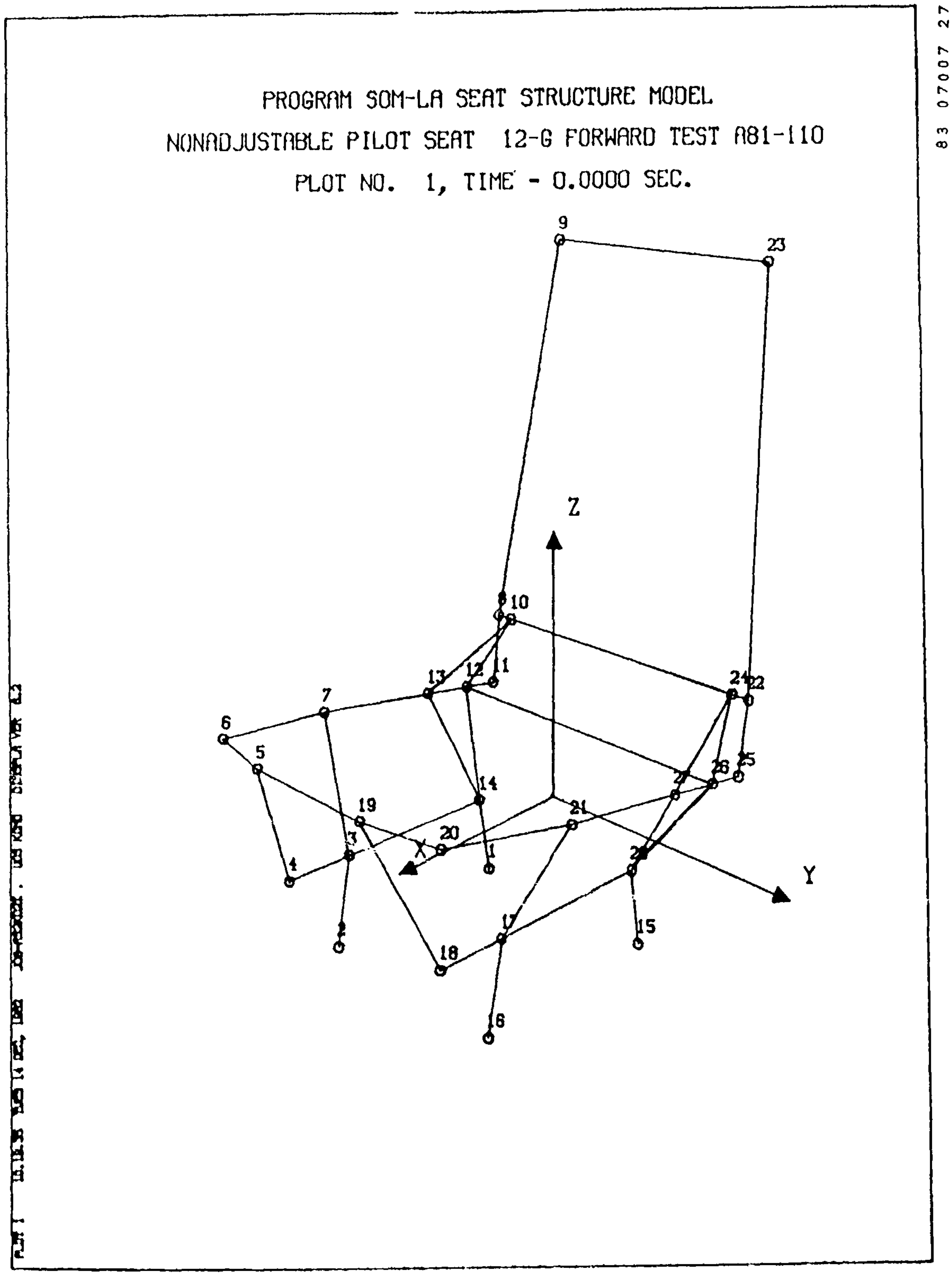


Figure A-25. Finite element model of seat structure.

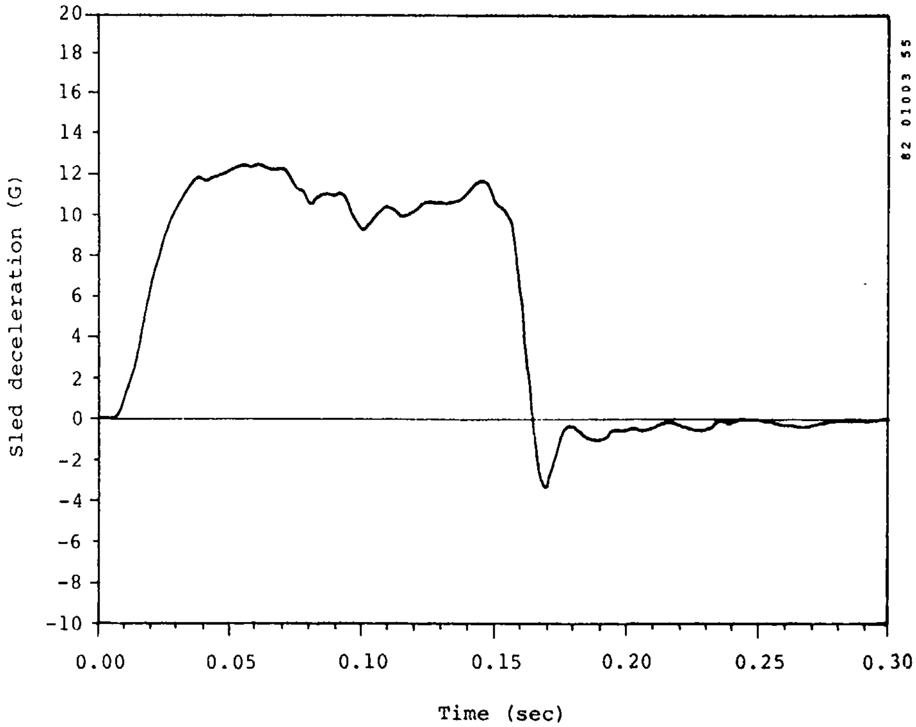


Figure A-26. Sled deceleration, CAMI general aviation seat test example.

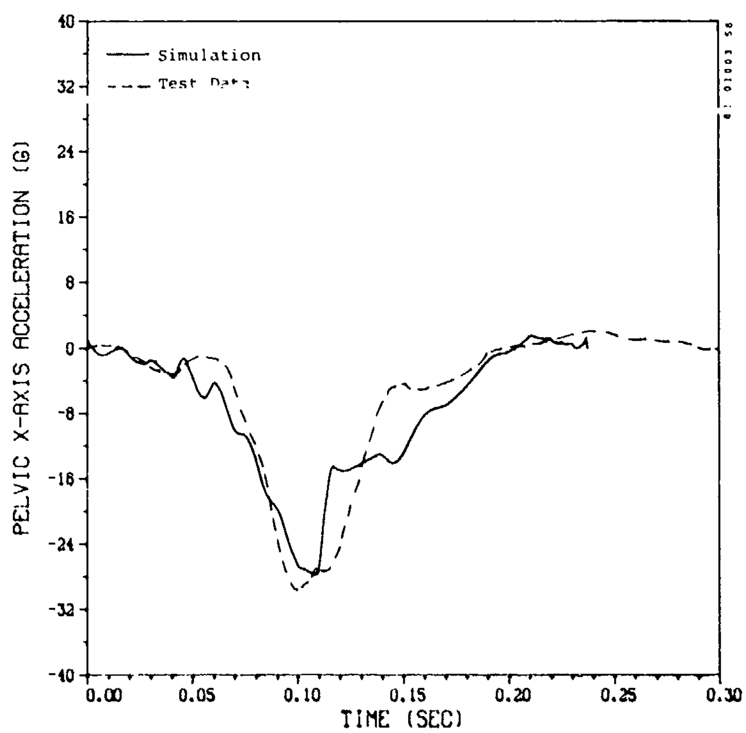


Figure A-27. General aviation seat test example, pelvis x-acceleration.

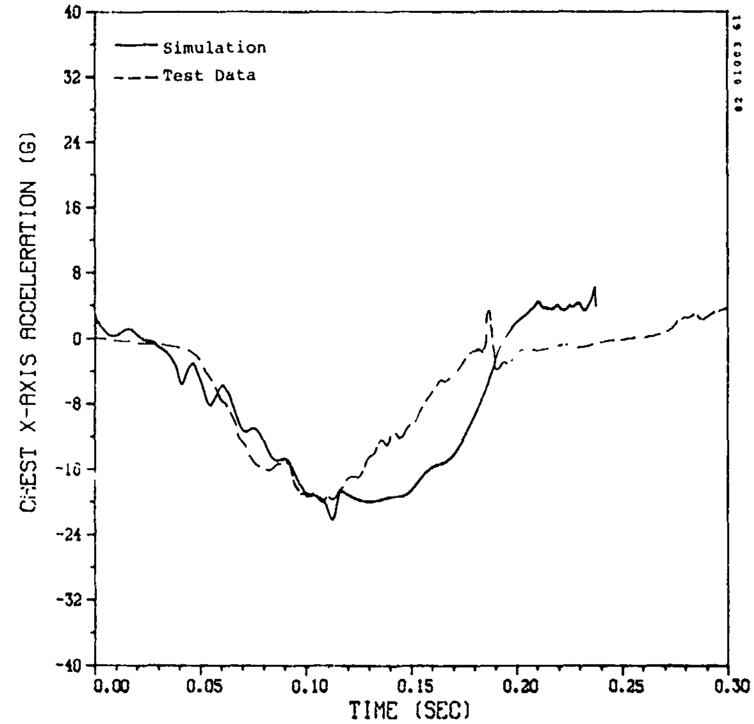


Figure A-28. General aviation seat test example, chest x-acceleration.

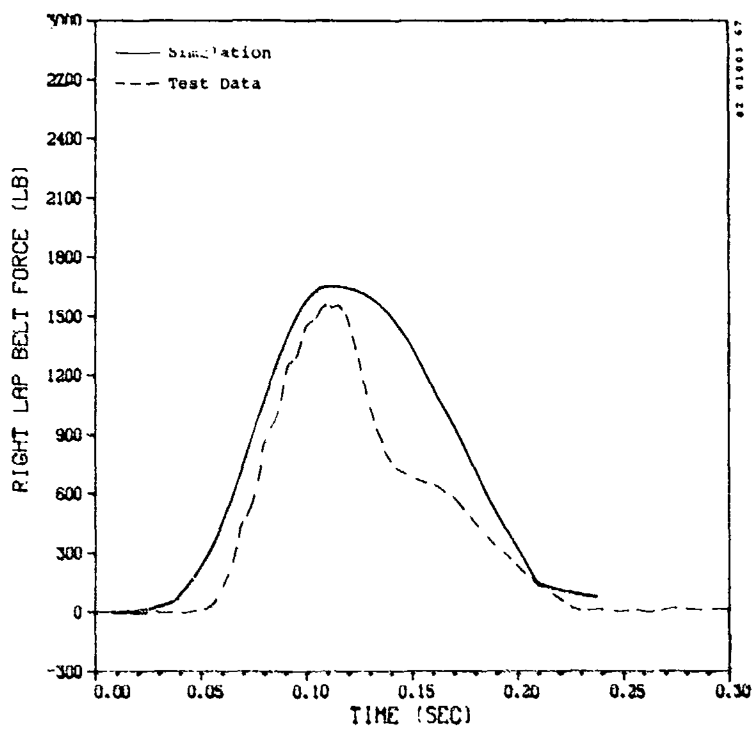


Figure A-29. General aviation seat test example, right lap belt force.

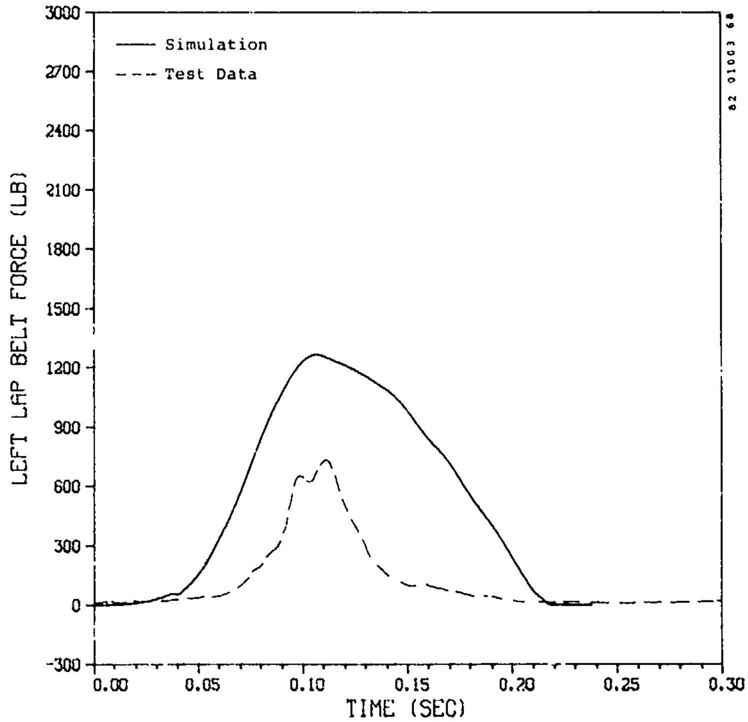


Figure A-30. General aviation seat test example, left lap belt force.

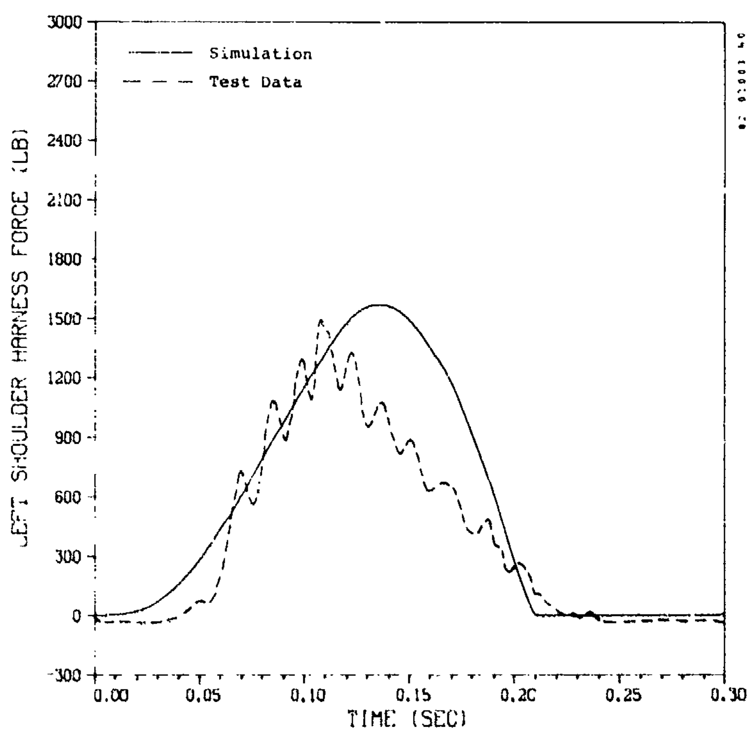
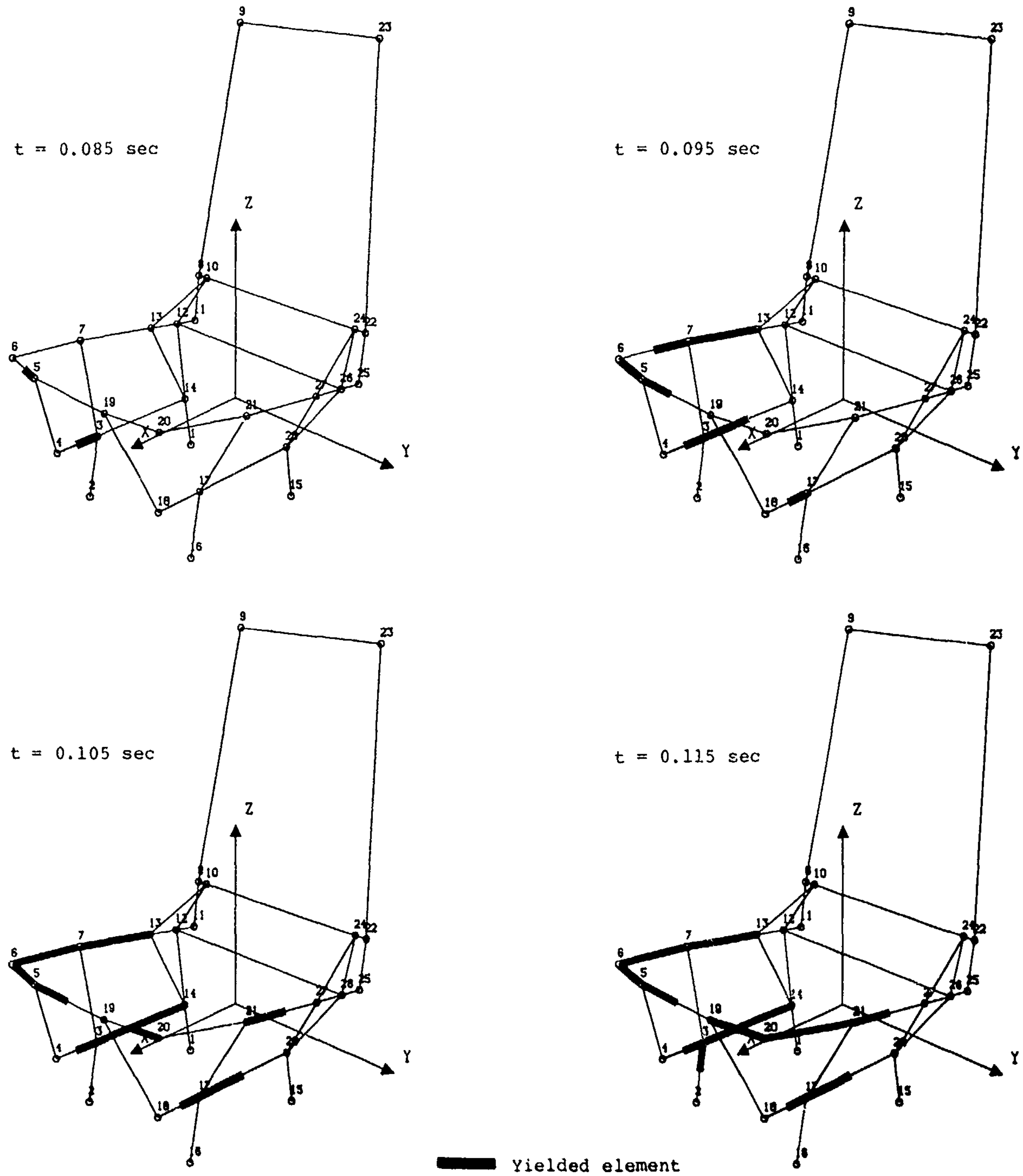
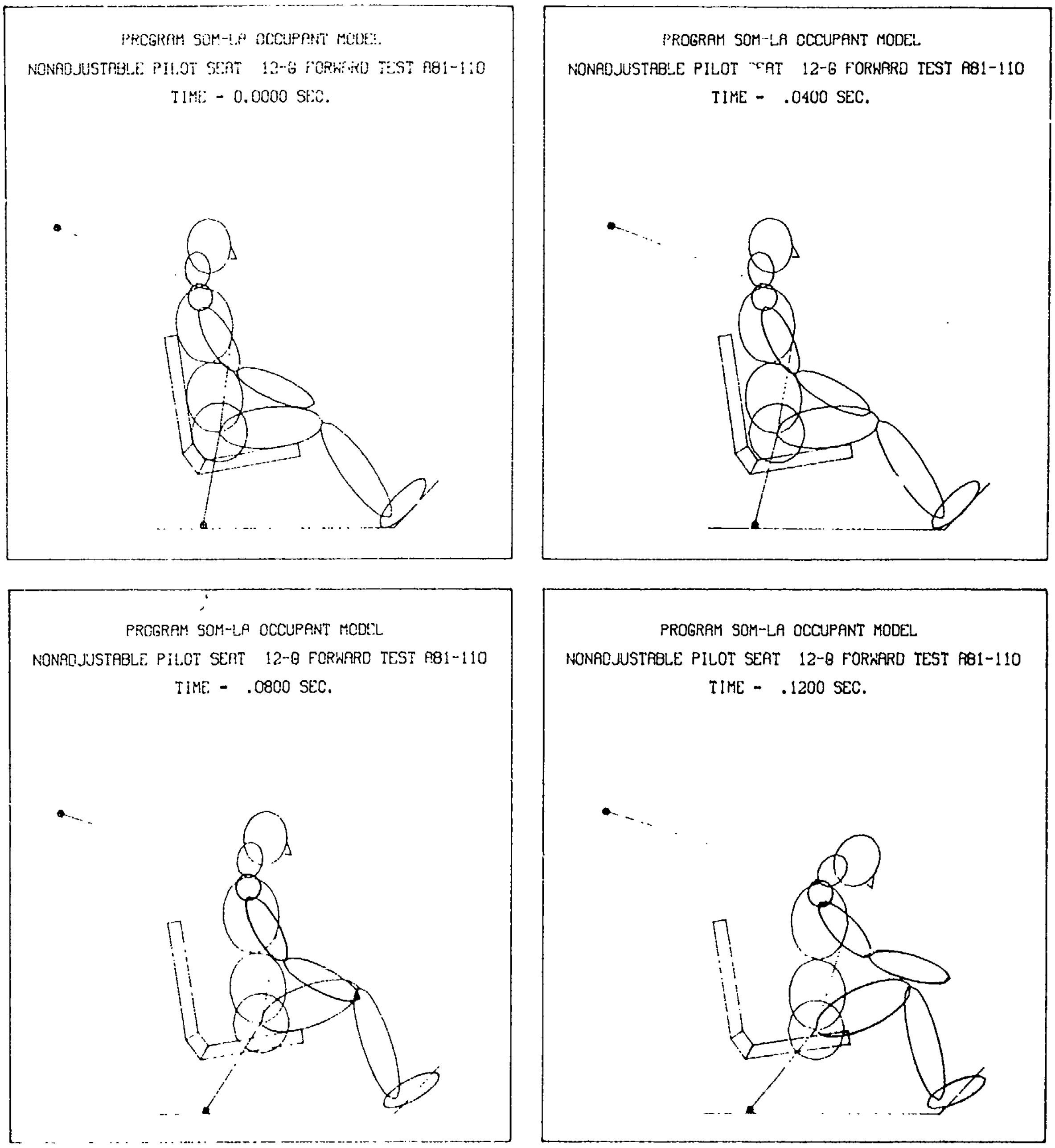


Figure A-31. General aviation seat test example, shoulder belt force.



83 07007 04

Figure A-32. General aviation seat test example, predicted progression of plastic deformation.



82 0:003 53

Figure A-33. General aviation seat Test A81-110, predicted occupant position.

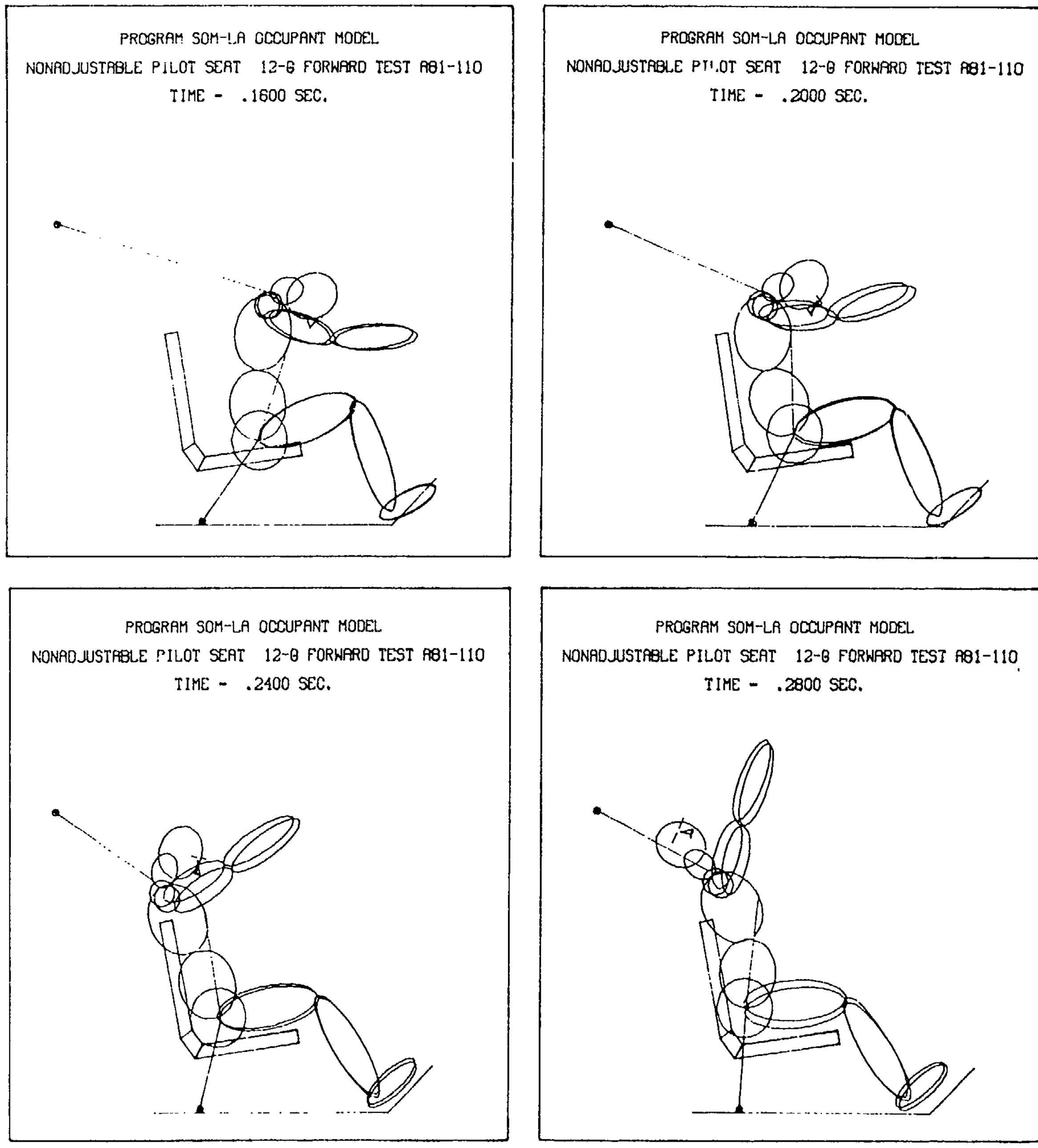


Figure A-33 (Contd). General aviation seat Test A81-110, predicted occupant position.

TABLE A-2. EXECUTION TIMES FOR THREE SIMULATIONS RUN WITH PROGRAM SOM-LA, JULY 1983

Simulation Case	1983 Occupant Model	Seat Structure DOF	Simulation Time (sec)	CPU Time (min)	
				CDC Cyber 175	DEC VAX 11/750
Energy-absorbing Helicopter Seat; 5-Point Restraint; 43.5-ft/sec, 41.5-G Vertical Impact	2D	2	0.250	0.22	6.03
CAMI Tubular-Leg Validation Test Seat; 4-Point Restraint; 44-ft/sec, 9.25-9.05-G Longitudinal Impact	2D	100	0.276	5.87	70.03
General Aviation Seat, 3-Point Restraint; 50-ft/sec, 12.4-G Longitudinal Impact	3D	172	0.235	18.24	100.40

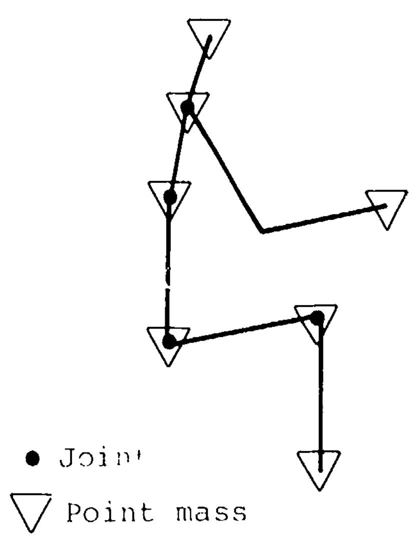


Figure A-34. PROMETHEUS occupant model.

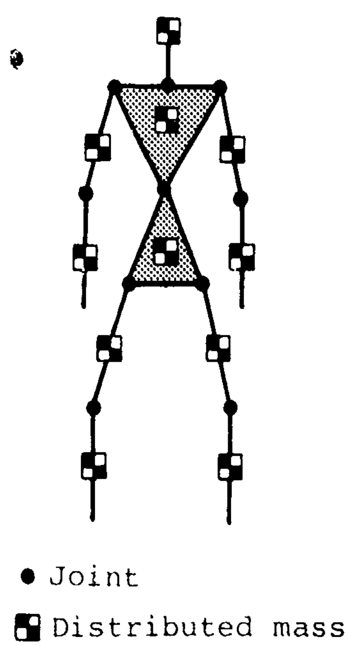
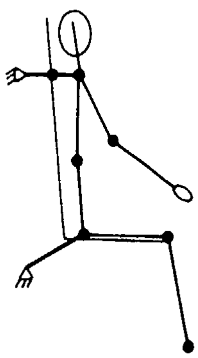


Figure A-35. PROMETHEUS II occupant model.

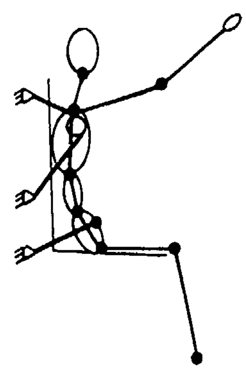
Old PROMETHEUS



Features

- Seven-segment articulation
- Rigid hinge links
- Belts pinned to joints
- Limited belt anchors

New PROMETHEUS III



83 07007 23

Features

- Submarining
  - Pelvis rotation
  - Buckle position
- Spinal changes
  - Nine-segment articulation
  - Compression/shear loads
  - Compressible lumbar/neck
- Improved restraint/seat modeling
  - Optional anchors
  - Added strands
  - Harness/belt slip
  - Friction
  - Viscosity
  - Cushioning/stretch
- Improved input definition
- Improved graphic/tabular output
- Added output force/torque/ velocity/acceleration
- Initial positioning automated

Figure A-36. PROMETHEUS III refinements (from reference A-17).

Pelvis - Design Interactions

- Angle
- Length
- Center of Mass
- Stiffness
- Friction

Back - Stiffness

- Erectness
- Compression

Belts - Anchor Points/Angles

- Location/Position on Body
- Mass Properties
- Damping Tension
- Stretch
- Slack
- Length
- Friction

Seat Pan - Angle

- Friction
- Cushioning
- Viscosity

Seat Back - Angle

- Cushioning
- Viscosity

A.2.3 COMPARATIVE EVALUATION OF SEAT/OCCUPANT SIMULATION MODELS. PROMETHEUS III appears to include most of the features desirable for helicopter crashworthiness evaluation, with the exception of three-dimensional capability, thus precluding its use in analysis of side-facing seats, three-point restraint systems, and non-symmetric impacts. However, its proprietary nature and limited available documentation prevented a complete evaluation.

SOM-LA, in a July 1983 version distributed to the FAA and several aircraft manufacturers, has been run successfully on CDC, IBM, and DEC computer systems. It has three-dimensional capability and all output features generally considered to be desirable for seat and restraint system evaluation.

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APPENDIX B

CODES USED FOR COMPLETING
ACCIDENT EVALUATION WORKSHEET

Case Number: The date of the accident and FAA registration numbers are used as a case number to identify each accident.

Model: Self explanatory

DMG: Damage Classification

- D - Destroyed
- S - Substantial
- M - Minor
- N - None

Terrain: This entry describes the type of terrain at the accident site. Some examples of the types of terrain and codes are listed below:

Code	Code
A - Mountainous	J - Plowed
B - Hilly	K - Water
C - Rolling	L - Sloped
D - Level, flat	M - Snow
E - Frozen	P - Paved
F - Rocky	R - Off-shore Rig
G - Sandy	S - Soft
H - Dense with trees	Y - Other
I - City Area	Z - Unknown

Fire: If fire was a factor in the accidents, a coded entry is made to describe the type of fire.

Code

- P - Postcrash
- I - Inflight
- G - Ground, not associated with the accident
- X - Unknown

A/C Wt: Aircraft weight. The maximum gross weight of each aircraft is used to determine its weight classification as listed below:

Code		Code	
A	0-2000 lb	H	8001-9000 lb
B	2001-3000	I	9001-10000
C	3001-4000	J	10001-11000
D	4001-5000	K	11001-12000
E	5001-6000	L	12001-13000
F	6001-7000	M	13001-16000
G	7001-8000	N	16001-25000
		O	25001+

Seats: Number of seats in each helicopter, including the crew.

Code

A - 1-3 Seats
B - 4-10
C - 11-20
D - 21+

Survivability: Survivable (S), partially survivable (P), or non-survivable (N), or with insufficient data to determine impact conditions: survivable (1), partially survivable (2), non-survivable (3), or unknown (4).

Injuries: These data are taken directly from the NTSB computer file and indicate the number and severity of injuries only. The type and cause of injuries are recorded separately on the accident evaluation worksheet.

Fatal - Number of occupants with fatal injuries.

Serious - Number of occupants with serious injuries.

Minor - Number of occupants with minor injuries.

None - Number of occupants uninjured.

On Board - Total number of occupants.

Operational Condition: This section describes the conditions, such as kind of flying, phase of operation, and type of accident.

Accident Type #1 - Describes the principal or primary event that occurred leading to, or causing the accident. The accident types and definitions of NTSB are used:

Code

A - Ground-water loop or swerve
B - Dragged wingtip, pad, or float
C - Wheels-up
D - Wheels-down landing in water
E - Gear collapsed
F - Gear retracted
G - Hard landing
H - Nose over/down
I - Rollover
J - Overshoot
K - Undershoot
L - Collision with aircraft
M - Collision with ground/water
N - Collided with:

0 - Wires/poles
1 - Trees
2 - Residences
3 - Other buildings
4 - Fence, Fenceposts
5 - Electronic towers, guy wires
6 - Runway or approach light
7 - Airport hazard
8 - Animals, livestock
9 - Crops

A - Flagman, loader
B - Ditches
C - Snowbank
D - Parked aircraft
E - Automobile
F - Dirt bank
Y - Other

P - Bird strike
Q - Stall
R0 - Fire or explosion in flight
R1 - Fire or explosion
S0 - Airframe failure in flight
S1 - Airframe failure on ground
T - Engine tearaway
U - Engine failure or malfunction
V2 - Tail rotor failure
V3 - Main rotor failure
W - Rotor accident to person
X - Jet intake/exhaust accident to person
Y - Jet/rotor blast
Z - Turbulence

0 - Hail damage to aircraft
1 - Lightning strike
2 - Evasive maneuver
3 - Uncontrolled altitude deviation
4 - Ditching
5 - Missing aircraft, not recovered
6 - Miscellaneous
7 - Undetermined

Accident Type #2 - In some instances, a second accident type is reported to give a better indication of what occurred. The same codes listed for Accident Type #1 will be used for Accident Type #2.

Phase of Operation #1 - Describes the phase of flight at the time the first accident type occurred. The broad categories and codes are listed below. Additional coding may be used to further define the flight phase in the same way as the NTSB.

Code	Code
A - Static	D - Inflight
B - Taxi	E - Landing
C - Takeoff	

Phase of Operation #2 - This phase is the same as defined for #1 except it is associated with accident Type #2.

Kind of Flying - The codes and definitions established by the NTSB are used to describe the kind of flying each aircraft was involved in at the time of the accident. Some examples of the kind-of-flying codes are listed below:

Code

AO - Instructional - dual
B2 - Noncommercial - business
CI - Commercial - air taxi
DA - Experimentation

Crash Environment: Describes the crash kinematics present at time of impact.

Airspeed - Airspeed of helicopter measured in knots at time of occurrence is used if known (same code as sink rate except in knots).

Flight Path Velocity - Velocity helicopter was traveling along the flight path measured in knots is used if known (same code as sink rate except in knots).

Flight Path Angle-Direction - The angle between the helicopter flight path and the horizon at the moment of impact. The angle and direction are coded as shown on the following page.

Code	Degrees	Code	Direction
0	0		
A	1-10	U	Up
B	11-20	D	Down
C	21-30	Z	Level
D	31-45		
E	46-60		
F	61-75		
G	76-90		
H	91-120		
I	121-150		
J	151-180		
X	Unknown		

Sink Rate: Velocity of helicopter in the vertical direction measured in feet per second.

Code	FPS	Code	FPS
0	0		
A	1-5	G	31-35
B	6-10	H	36-40
C	11-15	I	41-50
D	16-20	J	51-60
E	21-25	K	61+
F	26-30	X	Unknown

A/C Attitude: The aircraft attitude at impact, including pitch, roll, and yaw angles and directions is computed and coded as shown below.

Code	Degrees	Code	Direction
0	0		
A	0-10	R	Right
B	11-20	L	Left
C	21-30	D	Down
D	31-45	U	Up
E	46-60	Z	Level
F	61-75		
G	76-90		
H	91-120		
I	121-150		
J	151-180		
X	Unknown		

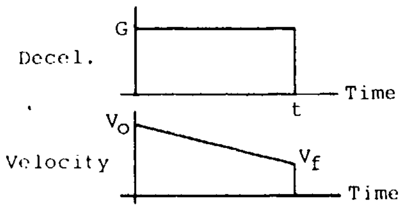
APPENDIX C

DECELERATION EQUATIONS COMMONLY USED IN ACCIDENT RECONSTRUCTION

DECELERATION EQUATIONS

FOR THE CASE $V_f \neq 0$

I. RECTANGULAR PULSE



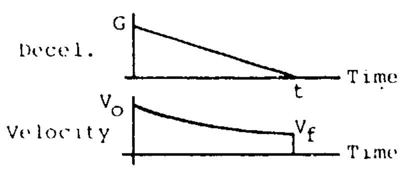
Pulse Duration: $t = \frac{V_o - V_f}{32.2G}$

Deceleration Level: $G = \frac{V_o^2 - V_f^2}{64.4G}$

Stopping Distance: $S = \frac{V_o^2 \quad V_f^2}{64.4G}$

Or: $S = V_o t - \frac{32.2Gt^2}{2}$

II. TRIANGULAR PULSE NO.1



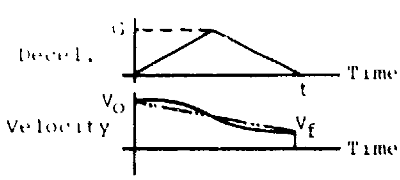
Pulse Duration: $t = \frac{2(V_o - V_f)}{32.2G}$

Deceleration Level: $G = \frac{2V_o^2 + 2V_oV_f - 4V_f^2}{96.6S}$

Stopping Distance: $S = \frac{2V_o^2 + 2V_oV_f - 4V_f^2}{}$

Or: $S = V_o t - \frac{32.2Gt^2}{3}$

III. TRIANGULAR PULSE NO. 2



Pulse Duration: $t = \frac{2(V_o - V_f)}{32.2G}$

Deceleration Level: $G = \frac{V_o^2 - V_f^2}{32.2S}$

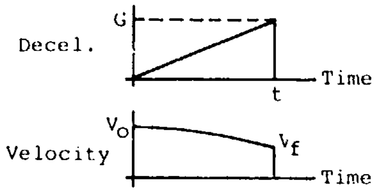
Stopping Distance: $S = \frac{V_o^2 \quad V_f^2}{32.2G}$

Or: $S = V_o t - \frac{32.2Gf^2}{4}$

DECELERATION EQUATIONS

FOR THE CASE $V_f \neq 0$

IV. TRIANGULAR PULSE NO. 3



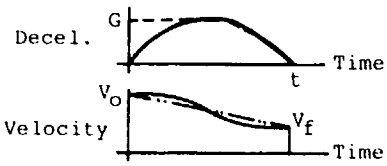
Pulse Duration: $$t = \frac{2(V_o - V_f)}{32.2G}$$

Deceleration Level: $$G = \frac{4V_o^2 - 2V_oV_f - 2V_f^2}{96.6S}$$

Stopping Distance: $$S = \frac{4V_o^2 - 2V_oV_f - 2V_f^2}{96.6G}$$

Or: $$S = V_ot - \frac{32.2Gt^2}{6}$$

V. HALF SINE PULSE



Pulse Duration: $$t = \frac{1.57\ (V_o - V_f)}{32.2G}$$

Deceleration Level: $$G = \frac{0.7854\ (V_o^2 - V_f^2)}{32.2S}$$

Stopping Distance: $$S = \frac{0.7854\ (V_o^2 - V_f^2)}{32.2S}$$

Or: $$S = V_ot - \frac{32.2Gt^2}{3.14}$$

APPENDIX D

SAMPLE CASE TO DEMONSTRATE ACCIDENT RECONSTRUCTION

SUMMARY: A small, piston-powered helicopter, modified for single-seat agricultural operations, was being used to seed the median of an interstate highway. The pilot stated that he was beginning a seeding run at approximately 20 ft AGL with an indicated airspeed of 40 mph with a 7 knot headwind. The pilot failed to see the three-phase power line crossing the highway. The rotor mast and rotor head contacted the three strands of wire and severed them. The aircraft continued along the median for 51 ft past the initial wire contact point, where initial ground contact was made. Following initial ground contact, the helicopter slid an additional 51 ft then rolled onto the right side coming to rest 135 degrees counterclockwise to the flight path. Ground scars occurred only at the point of initial ground contact.

AIRCRAFT DAMAGE: The aircraft was destroyed. The upper transmission rotor mast and rotor head had separated from the lower transmission, but all components were with the wreckage. Wire was found wrapped around the rotor mast. Both landing gear crosstubes were bent upward approximately 6 in. due to vertical impact forces. The left skid was undeformed except that the forward 10 in. were broken off, apparently from snagging as the aircraft slid. The right skid folded under the aircraft as it rolled over. The cockpit maintained its structural integrity during the rollover.

SURVIVAL ASPECTS: The pilot was wearing a lap belt, dual shoulder harness, and a helmet at the time of the accident. The pilot was uninjured, however the helmet received two deep gashes on the top left side. The investigator suggested that the helmet prevented a serious head injury.

ACCIDENT KINEMATICS: Figure D-1 shows a sketch of the accident sequence. The ground scars at the initial contact point indicated that the aircraft impacted with zero degrees pitch, roll, and yaw. The forward velocity of the aircraft

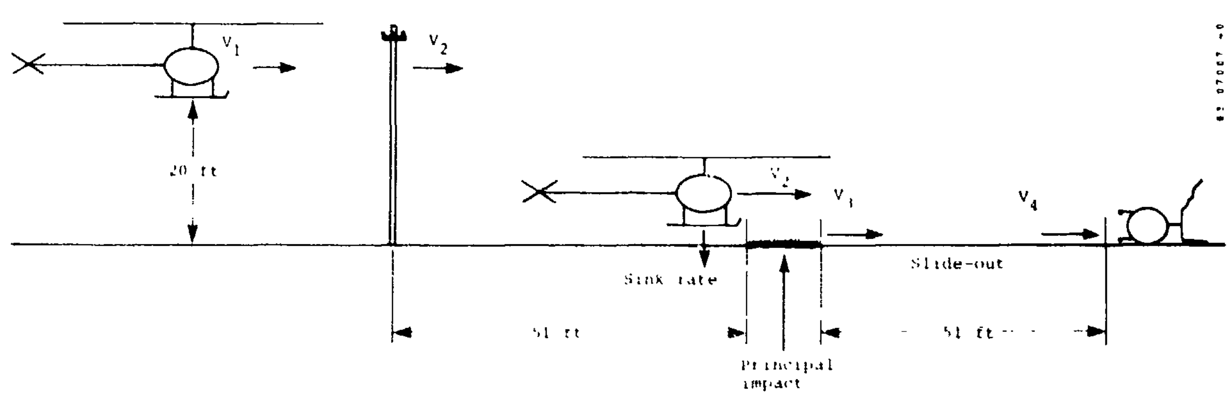


Figure D-1. Accident sequence.

relative to the ground at the time of the wire strike was calculated by subtracting the indicated airspeed from the headwind velocity:

$$V_1 = 59 \text{ ft/sec (40 mph)} - 12 \text{ ft/sec (7 knts)}$$
$$= 47 \text{ ft/sec}$$

The impact dynamics were estimated by working backwards from the final resting place of the aircraft. Just prior to coming to rest the helicopter had enough velocity to roll over onto its side without significant additional sliding. This velocity, V_4, was estimated to be 3 ft/sec. The slideout covered 51 ft with an assumed constant deceleration (as shown in figure 3 of section 2.1.3.2) of 0.4 G, which is a typical sliding coefficient of friction for ground contact (Reference 17). The distance traveled, S, during the slide is related to the initial and final velocity by the equation:

$$S = \frac{V_3^{\,2} - V_4^{\,2}}{2gG}$$

Therefore,

$$V_3 = \sqrt{2g\ SG + V_4^{\,2}}$$
$$= \sqrt{2(32.2 \text{ ft/sec}^2)(51 \text{ ft})(0.4g) + (3 \text{ ft/sec})^2}$$
$$= 36 \text{ ft/sec}$$

At this point it was necessary to make one assumption due to the complication of the wire strike, in order to solve a set of equations describing the initial impact. It was estimated that the impulsive force supplied by the wires slowed the aircraft by 5 ft/sec. Therefore, the aircraft velocity (V_2) just after the wires snapped was 42 ft/sec. This was used to estimate an average sink rate knowing that the aircraft height decreased 20 ft during the time that the aircraft traversed 51 ft at 42 ft/sec. The average sink rate is then:

$$\text{SINK RATE} = \frac{20 \text{ ft}}{(51 \text{ ft}/42 \text{ ft/sec})} = 16.5 \text{ ft/sec}$$

A symmetric triangular deceleration pulse was used to simulate the vertical impact conditions. Using a typical pulse duration of 0.065 sec (based on crash test data) the vertical deceleration pulse has the characteristics shown in Figure D-2. The stopping distance for the deceleration pulse is 6.5 in. which coincides with the observed gear deflection of approximately 6 in.

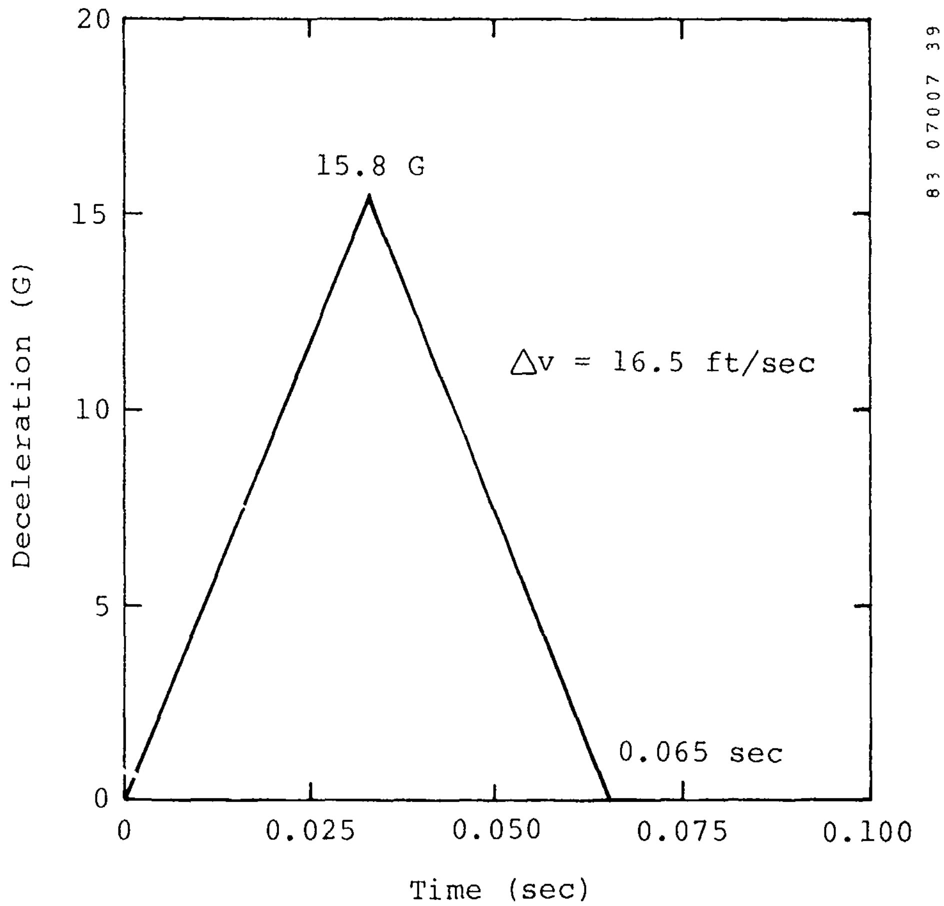


Figure D-2. Estimated vertical deceleration pulse for principal impact.

A first impression is that 16.5 ft/sec sink rate is too high, considering the observed damage to the skid gear. However, upon further examination it was noted that the aircraft is significantly below the design gross weight for the gear due to the airframe modifications (single seat cockpit) and fuel load at impact. The observed gear damage may have been reasonable considering the applied inertial loading.

A longitudinal force was simultaneously applied to the aircraft due to friction. Figure D-3 shows the longitudinal deceleration pulse, that is the vertical pulse multiplied by the coefficient of sliding friction, (0.4). The longitudinal aircraft velocity was decreased by 6.6 ft/sec during this initial impact. Figure D-4 lists the approximate impact parameters.

Additional iterations could have been conducted to refine the magnitude of the impact parameters. However, since the initial calculation was based on the pilot's estimate of height (20 ft) and velocity (40 mph), it was believed that further refinement was unjustified.

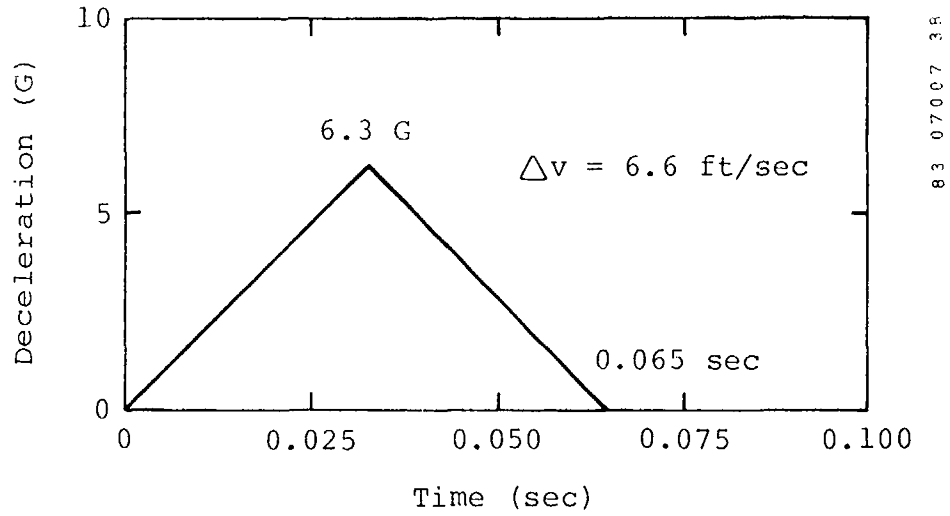


Figure D-3. Estimated longitudinal deceleration pulse for principal impact.

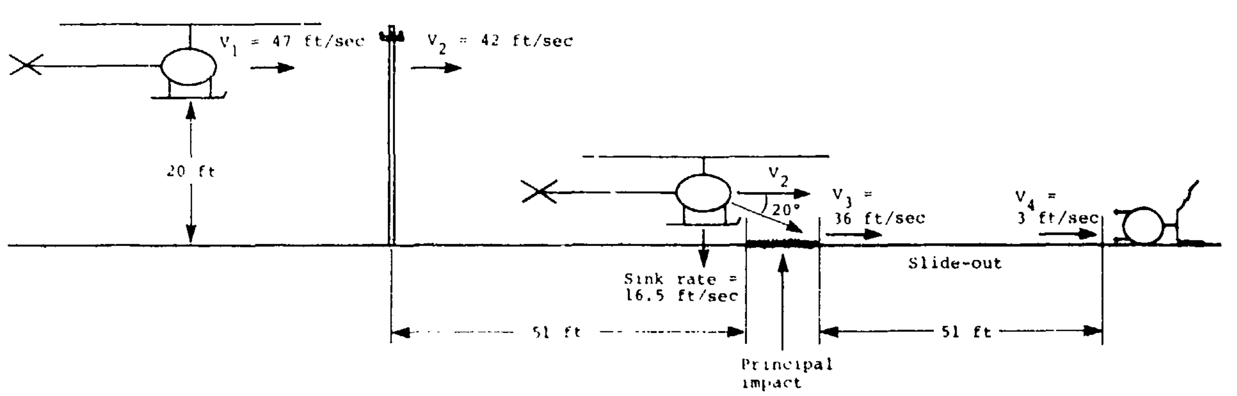


Figure D-4. Estimated aircraft velocity during accident sequence.

APPENDIX E

PITCH, ROLL, AND YAW ANGLE DISTRIBUTION BY WEIGHT CLASS

TABLE E-1. DISTRIBUTION OF PITCH ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS A

Angle (deg)	Direction Up	Level	Down	Total Number	Percent of Total	Cummulative Percent
0		33		33	32.7	32.7
1-10	26		12	38	37.6	70.3
11-20	11		4	15	14.8	85.1
21-30	1		0	1	1.0	86.1
31-45	1		3	4	4.0	90.1
46-60	1		2	3	3.0	93.1
61-75	0		0	0	0.0	93.1
76-90	0		2	2	2.0	95.1
91-120	0		1	1	1.0	96.1
121-150	0		3	3	3.0	99.1
151-180	0		1	1	1.0	100.1
			TOTAL	101	100.1	

TABLE E-2. DISTRIBUTION OF PITCH ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS B

Angle (deg)	Direction Up	Level	Down	Total Number	Percent of Total	Cummulative Percent
0		29		29	31.9	31.9
1-10	25		11	36	39.6	71.5
11-20	7		6	13	14.3	85.8
21-30	2		7	9	9.9	95.7
31-45	0		2	2	2.2	97.9
46-60	0		0	0	0.0	97.9
61-75	0		0	0	0.0	97.9
76-90	0		0	0	0.0	97.9
91-120	0		1	1	1.1	99.0
121-150	0		0	0	0.0	99.0
151-180	0		1	1	1.1	100.0
			TOTAL	91	100.1	

TABLE E-3. DISTRIBUTION OF PITCH ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS C

Angle (deg)	Direction: Up	Level	Down	Total Number	Percent of Total	Cummulative Percent
0		6		6	35.3	35.3
1-10	3		4	7	41.1	76.4
11-20	1		2	3	17.6	94.0
21-30	0		0	0	0.0	94.0
31-45	0		0	0	0.0	94.0
46-60	0		0	0	0.0	94.0
61-75	0		0	0	0.0	94.0
76-90	0		0	0	0.0	94.0
91-120	0		0	0	0.0	94.0
121-150	0		0	0	0.0	94.0
151-180	0		1	1	5.9	99.9
			TOTAL	17	99.9	

TABLE E-4. DISTRIBUTION OF PITCH ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS D

Angle (deg)	Direction: Up	Level	Down	Total Number	Percent of Total	Cummulative Percent
0		1		1	14.3	14.3
1-10	3		0	3	42.8	57.1
11-20	2		1	3	42.8	99.9
21-30	0		0	0	0.0	99.9
31-45	0		0	0	0.0	99.9
46-60	0		0	0	0.0	99.9
61-75	0		0	0	0.0	99.9
76-90	0		0	0	0.0	99.9
91-120	0		0	0	0.0	99.9
121-150	0		0	0	0.0	99.9
151-180	0		0	0	0.0	99.9
			TOTAL	7	99.9	

TABLE E-5. DISTRIBUTION OF ROLL ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS A

Angle (deg)	Direction: Right	Level	Left	Total Number	Percent of Total	Cummulative Percent
0		63		63	63.0	63.0
1-10	6		6	12	12.0	75.0
11-20	2		5	7	7.0	82.0
21-30	1		1	2	2.0	84.0
31-45	0		3	3	3.0	87.0
46-60	0		0	0	0.0	87.0
61-75	0		0	0	0.0	87.0
76-90	9		0	9	9.0	96.0
91-120	1		0	1	1.0	97.0
121-150	0		1	1	1.0	98.0
151-180	2		0	2	2.0	100.0
			TOTAL	100	100.0	

TABLE E-6. DISTRIBUTION OF ROLL ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS B

Angle (deg)	Direction: Right	Level	Left	Total Number	Percent of Total	Cummulative Percent
0		57		57	60.6	60.6
1-10	4		2	6	6.4	67.0
11-20	4		4	8	8.5	75.5
21-30	0		1	1	1.1	76.6
31-45	0		3	3	3.2	79.8
46-60	0		0	0	0.0	79.8
61-75	0		0	0	0.0	79.8
76-90	7		4	11	11.7	91.5
91-120	1		1	2	2.1	93.6
121-150	0		0	0	0.0	93.6
151-180	6		0	6	6.4	100.0
			TOTAL	94	100.0	

TABLE E-7. DISTRIBUTION OF ROLL ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS C

Angle (deg)	Direction Right	Level	Left	Total Number	Percent of Total	Cummulative Percent
0		9		9	52.9	52.9
1-10	1		5	6	35.3	88.2
11-20	0		1	1	5.9	94.1
21-30	0		0	0	0.0	94.1
31-45	0		0	0	0.0	94.1
46-60	0		0	0	0.0	94.1
61-75	0		0	0	0.0	94.1
76-90	0		1	1	5.9	100.0
91-120	0		0	0	0.0	100.0
121-150	0		0	0	0.0	100.0
151-180	0		0	0	0.0	100.0
			TOTAL	17	100.0	

TABLE E-8. DISTRIBUTION OF ROLL ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS D

Angle (deg)	Direction Right	Level	Left	Total Number	Percent of Total	Cummulative Percent
0		4		4	57.1	57.1
1-10	1		0	1	14.3	71.4
11-20	0		1	1	14.3	85.7
21-30	1		0	1	14.3	100.0
31-45	0		0	0	0.0	100.0
46-60	0		0	0	0.0	100.0
61-75	0		0	0	0.0	100.0
76-90	0		0	0	0.0	100.0
91-120	0		0	0	0.0	100.0
121-150	0		0	0	0.0	100.0
151-180	0		0	0	0.0	100.0
			TOTAL	7	100.0	

TABLE E-9. DISTRIBUTION OF YAW ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS A

Angle (deg)	Direction Right	Direction Level	Direction Left	Total Number	Percent of Total	Cummulative Percent
0		69		69	75.8	75.8
1-10	5		1	6	6.6	82.4
11-20	0		2	2	2.2	84.6
21-30	2		0	2	2.2	86.8
31-45	1		1	2	2.2	89.0
46-60	1		0	1	1.1	90.1
61-75	2		0	2	2.2	92.3
76-90	3		0	3	3.3	95.6
91-120	1		0	1	1.1	96.7
121-150	0		2	2	2.2	98.9
151-180	1		0	1	1.1	100.0
			TOTAL	91	100.0	

TABLE E-10. DISTRIBUTION OF YAW ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS B

Angle (deg)	Direction Right	Direction Level	Direction Left	Total Number	Percent of Total	Cummulative Percent
0		62		62	83.8	83.8
1-10	4		4	8	10.8	94.6
11-20	1		0	1	1.4	96.0
21-30	0		0	0	0.0	96.0
31-45	0		0	0	0.0	96.0
46-60	1		0	1	1.4	97.4
61-75	0		0	0	0.0	97.4
76-90	1		1	2	2.7	100.1
91-120	0		0	0	0.0	100.1
121-150	0		0	0	0.0	100.1
151-180	0		0	0	0.0	100.1
			TOTAL	74	100.1	

TABLE E-11. DISTRIBUTION OF YAW ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS C

Angle (deg)	Direction: Right	Direction: Level	Direction: Left	Total Number	Percent of Total	Cummulative Percent
0		12		12	70.5	70.5
1-10	3		2	5	29.4	99.9
11-20	0		0	0	0.0	99.9
21-30	0		0	0	0.0	99.9
31-45	0		0	0	0.0	99.9
46-60	0		0	0	0.0	99.9
61-75	0		0	0	0.0	99.9
76-90	0		0	0	0.0	99.9
91-120	0		0	0	0.0	99.9
121-150	0		0	0	0.0	99.9
151-180	0		0	0	0.0	99.9
			TOTAL	17	99.9	

TABLE E-12. DISTRIBUTION OF YAW ANGLE AND DIRECTION AT IMPACT FOR WEIGHT CLASS D

Angle (deg)	Direction: Right	Direction: Level	Direction: Left	Total Number	Percent of Total	Cummulative Percent
0		4		4	66.7	66.7
1-10	1		0	1	16.7	83.4
11-20	0		1	1	16.7	100.1
21-30	0		0	0	0.0	100.1
31-45	0		0	0	0.0	100.1
46-60	0		0	0	0.0	100.1
61-75	0		0	0	0.0	100.1
76-90	0		0	0	0.0	100.1
91-120	0		0	0	0.0	100.1
121-150	0		0	0	0.0	100.1
151-180	0		0	0	0.0	100.1
			TOTAL	6	100.1	

APPENDIX F

VERTICAL AND LONGITUDINAL IMPACT VELOCITY BY WEIGHT CLASS

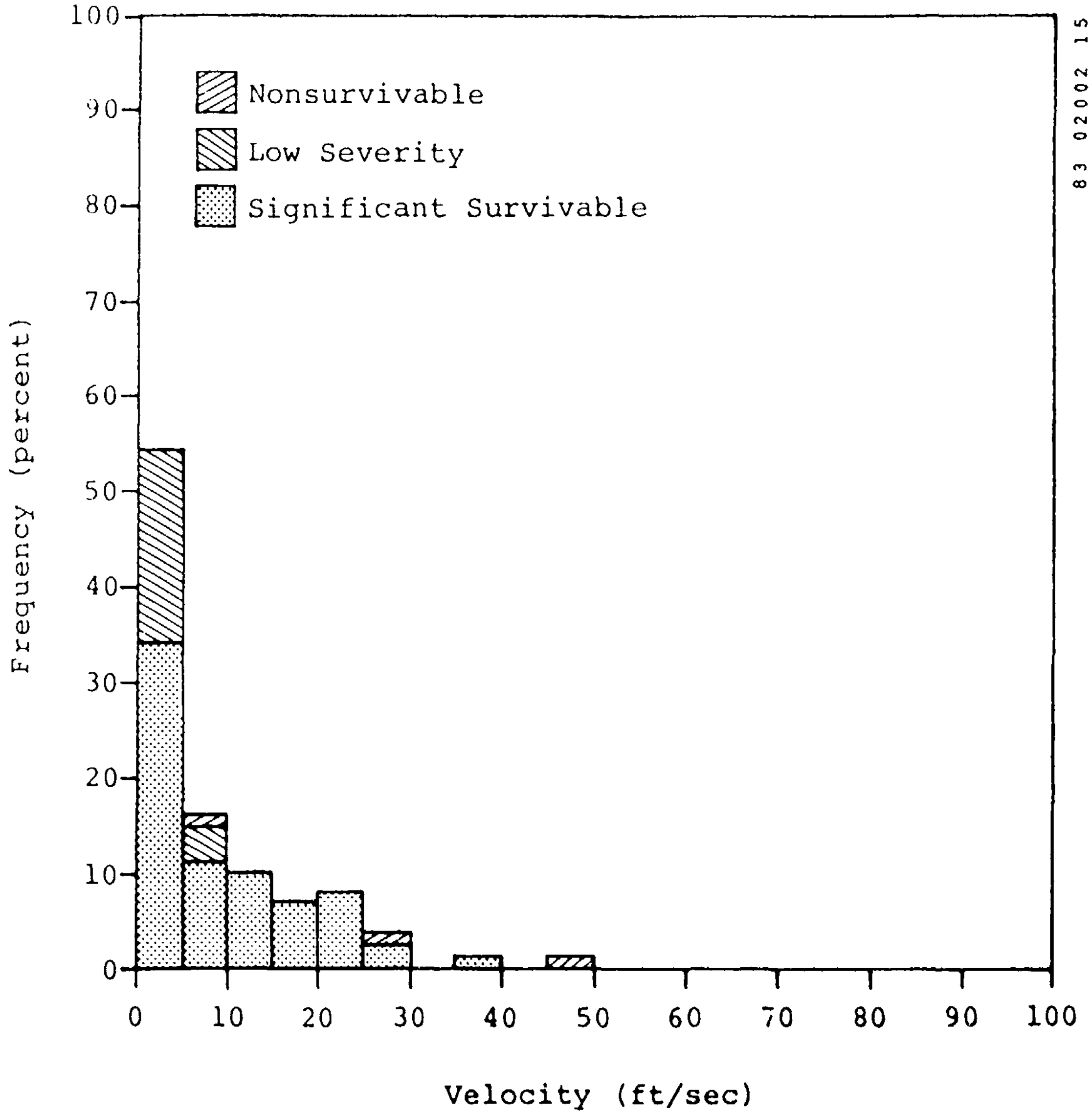


Figure F-1. Frequency of occurrence of vertical impact velocity, Weight Class A (89 accidents).

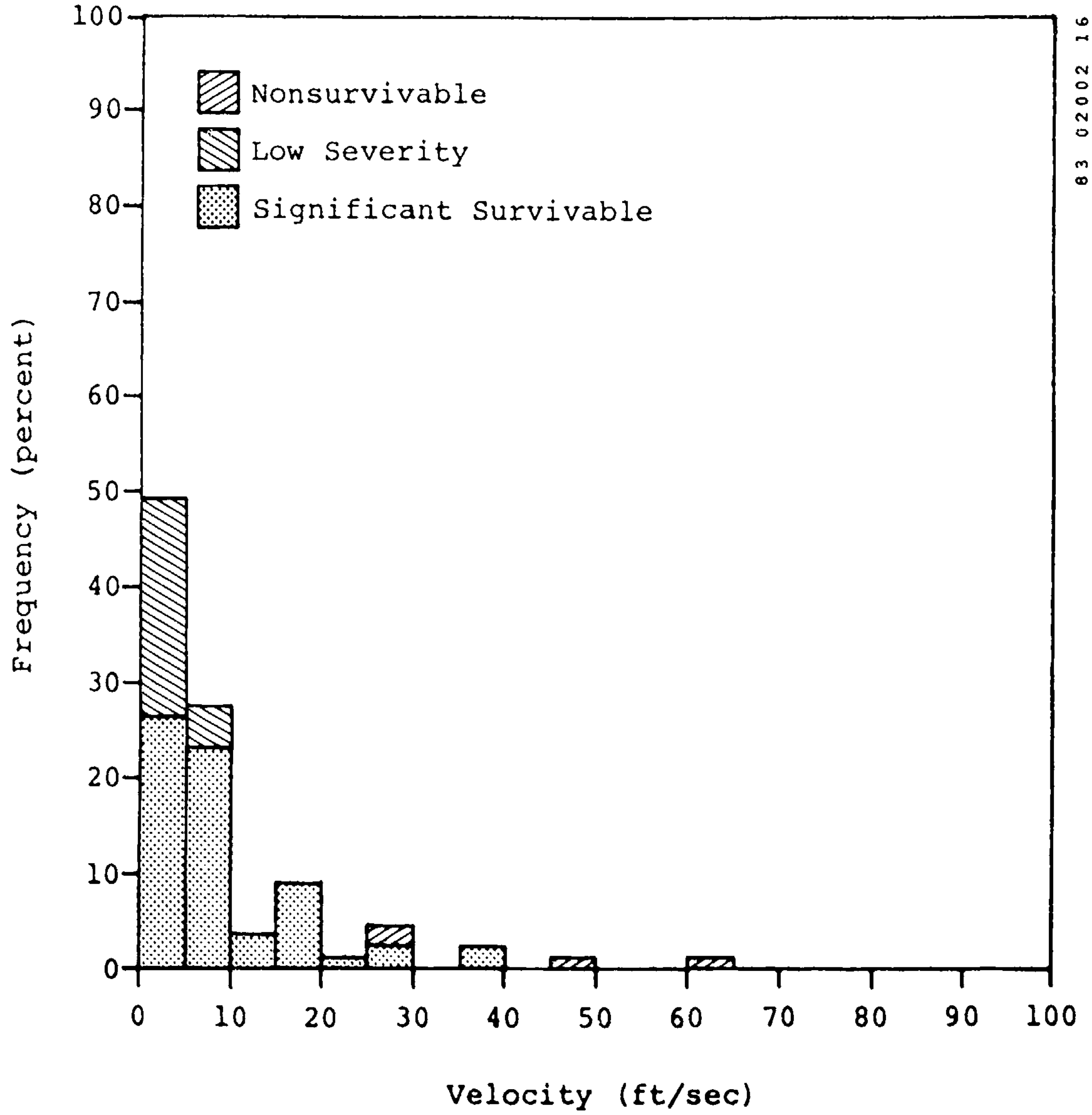


Figure F-2. Frequency of occurrence of vertical impact velocity, Weight Class B (87 accidents).

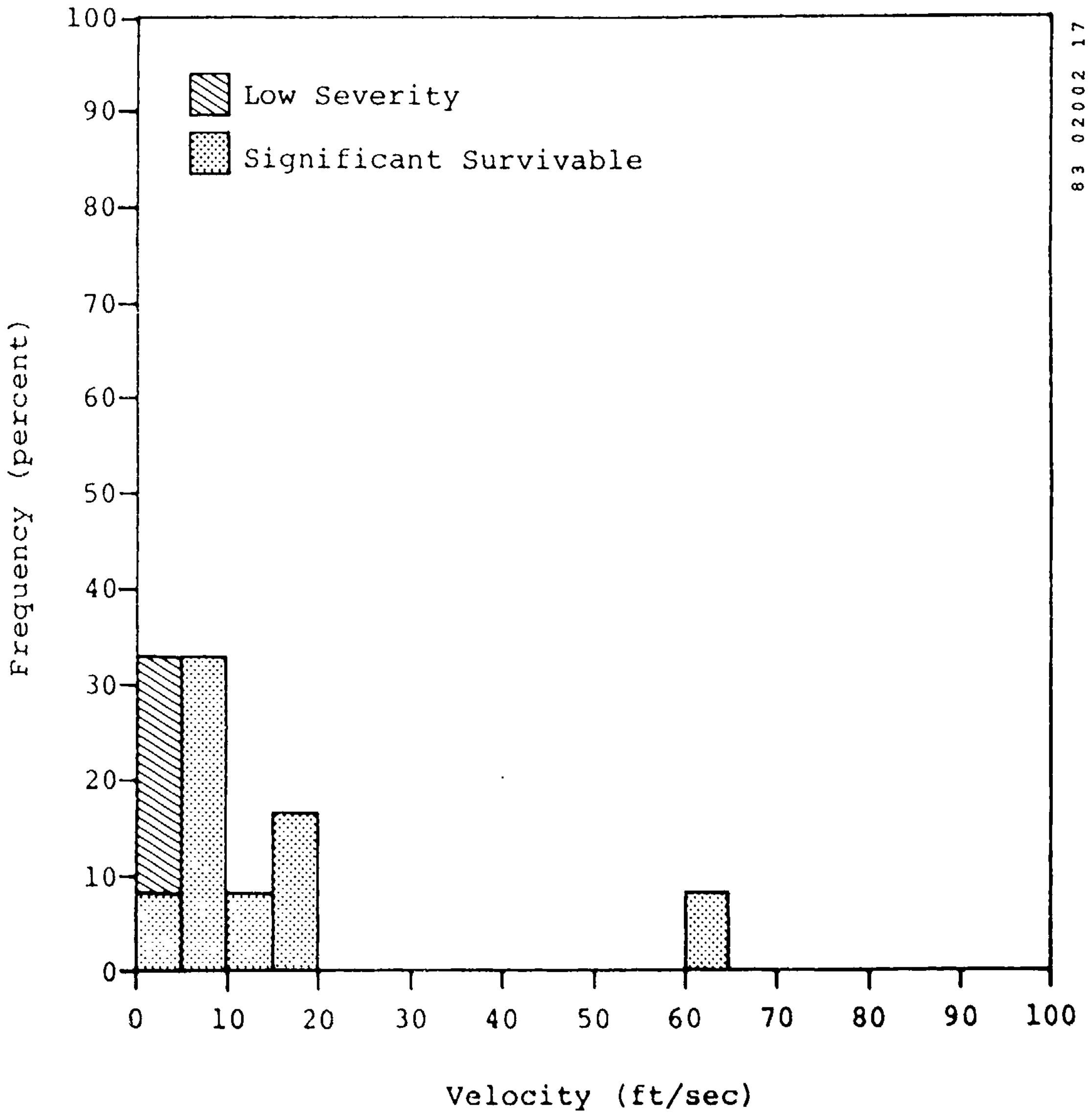


Figure F-3. Frequency of occurrence of vertical impact velocity, Weight Class C (12 accidents).

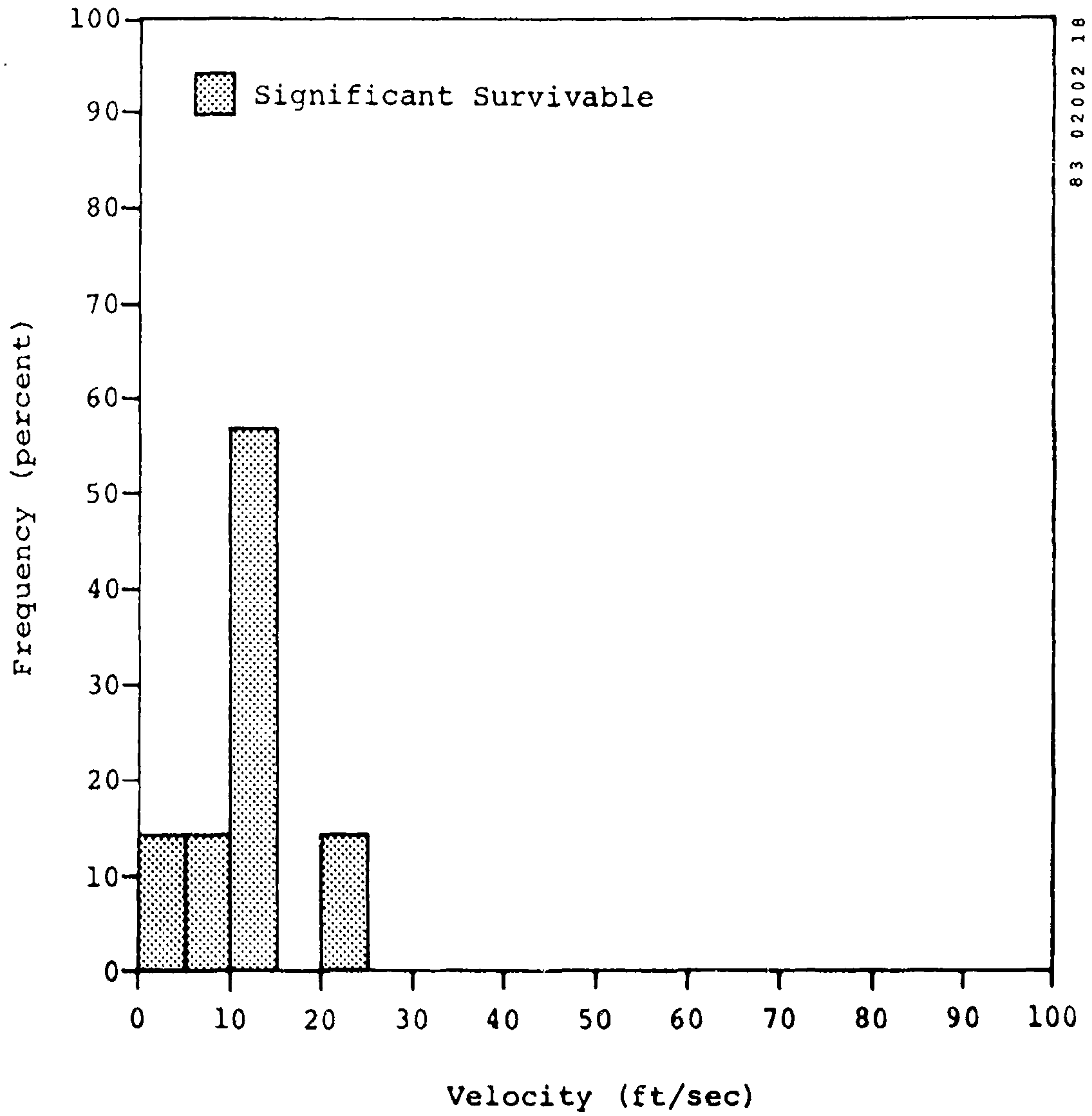


Figure F-4. Frequency of occurrence of vertical impact velocity, Weight Class D (7 accidents).

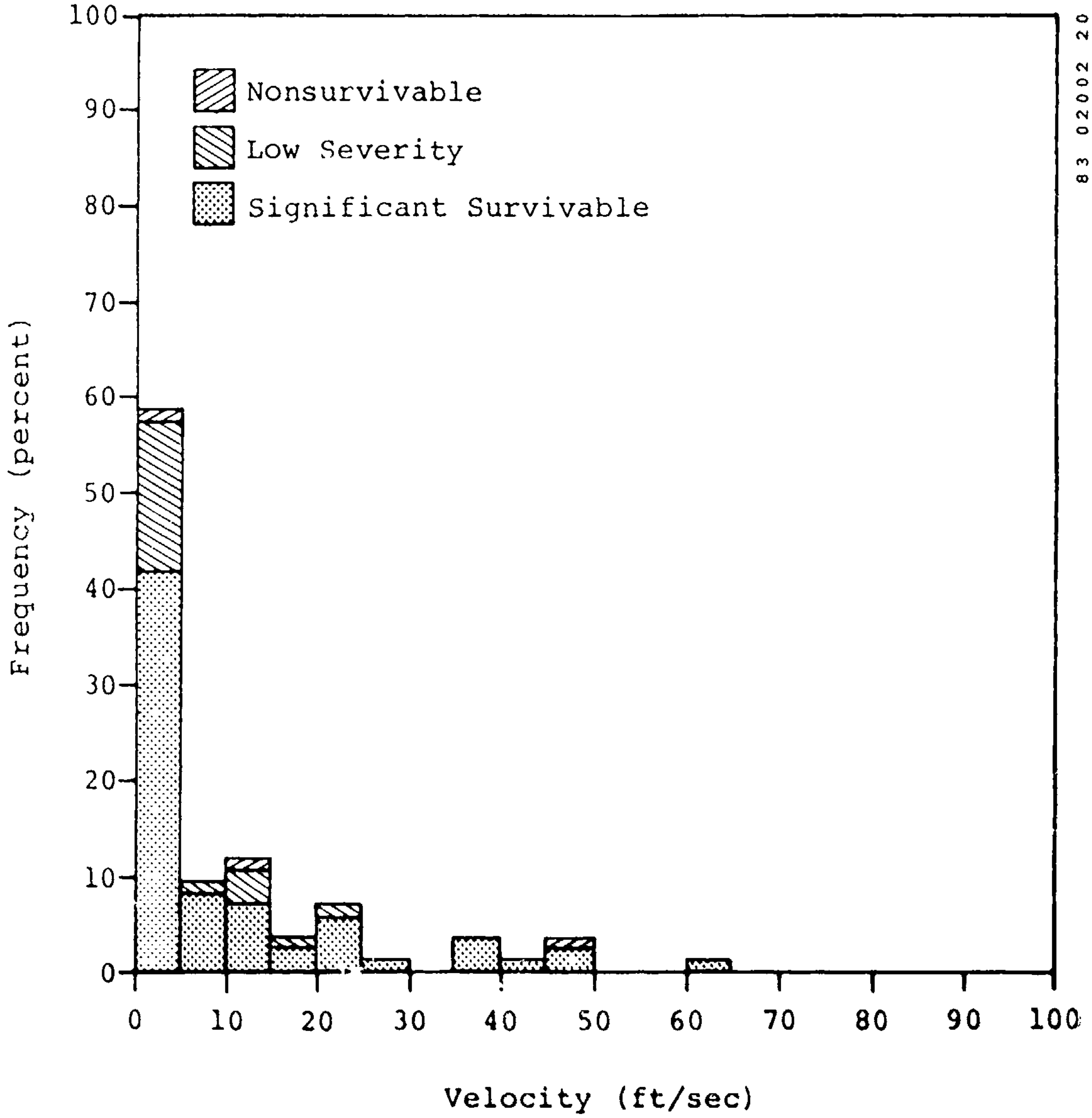


Figure F-5. Frequency of occurrence of longitudinal impact velocity, Weight Class A (87 accidents).

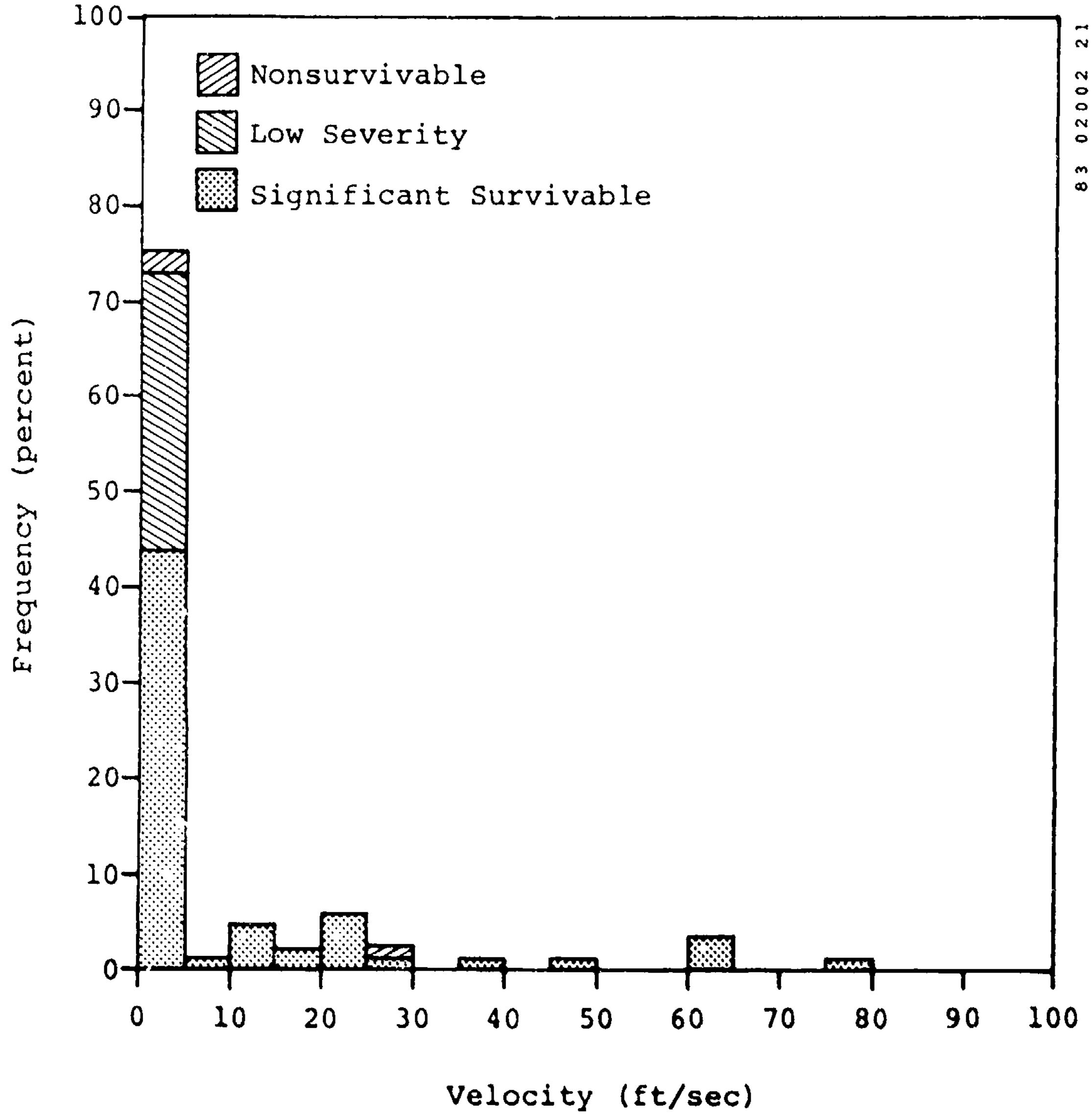


Figure F-6. Frequency of occurrence of longitudinal impact velocity, Weight Class B (82 accidents).

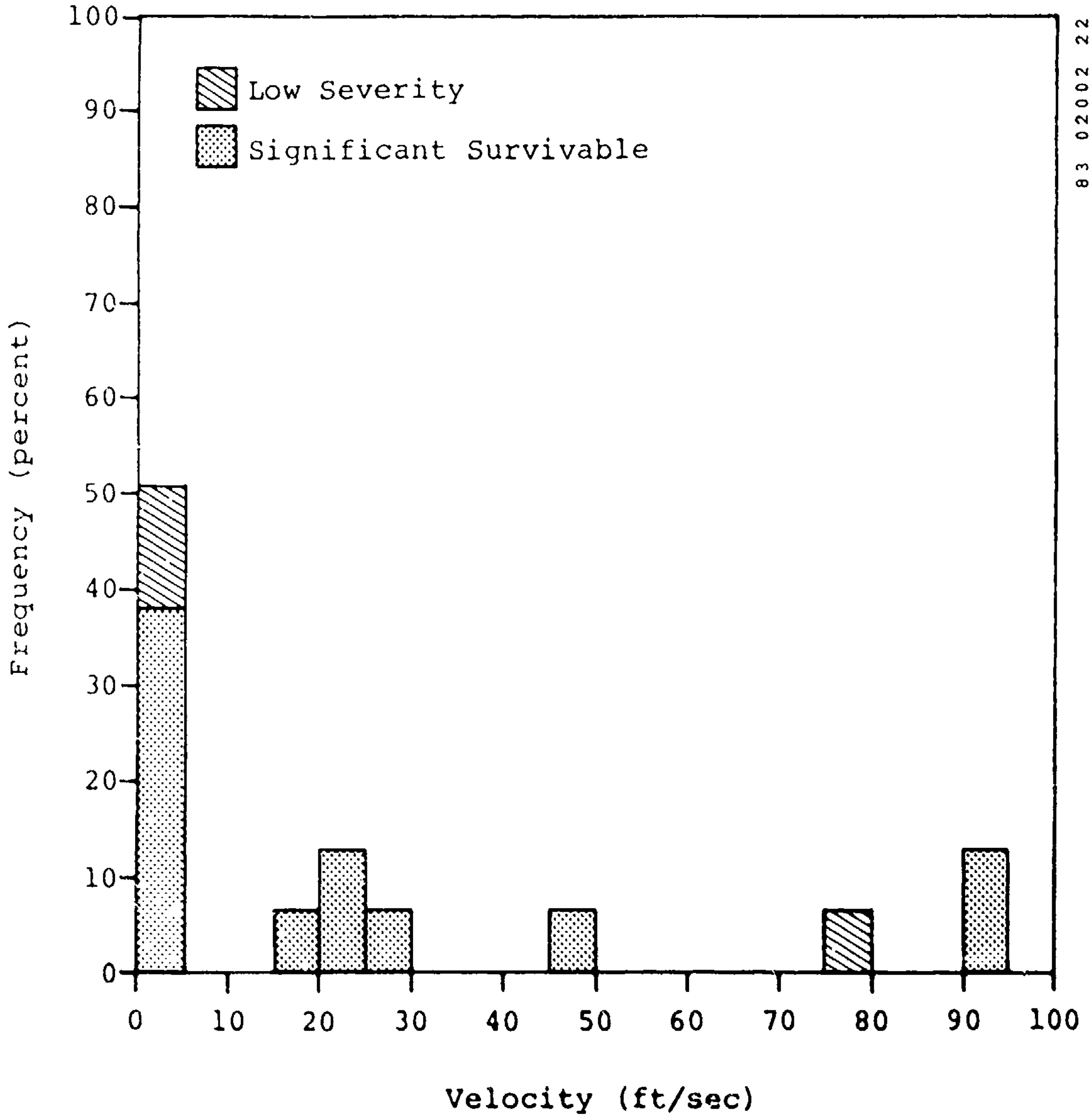


Figure F-7. Frequency of occurrence of longitudinal impact velocity, Weight Class C (16 accidents).

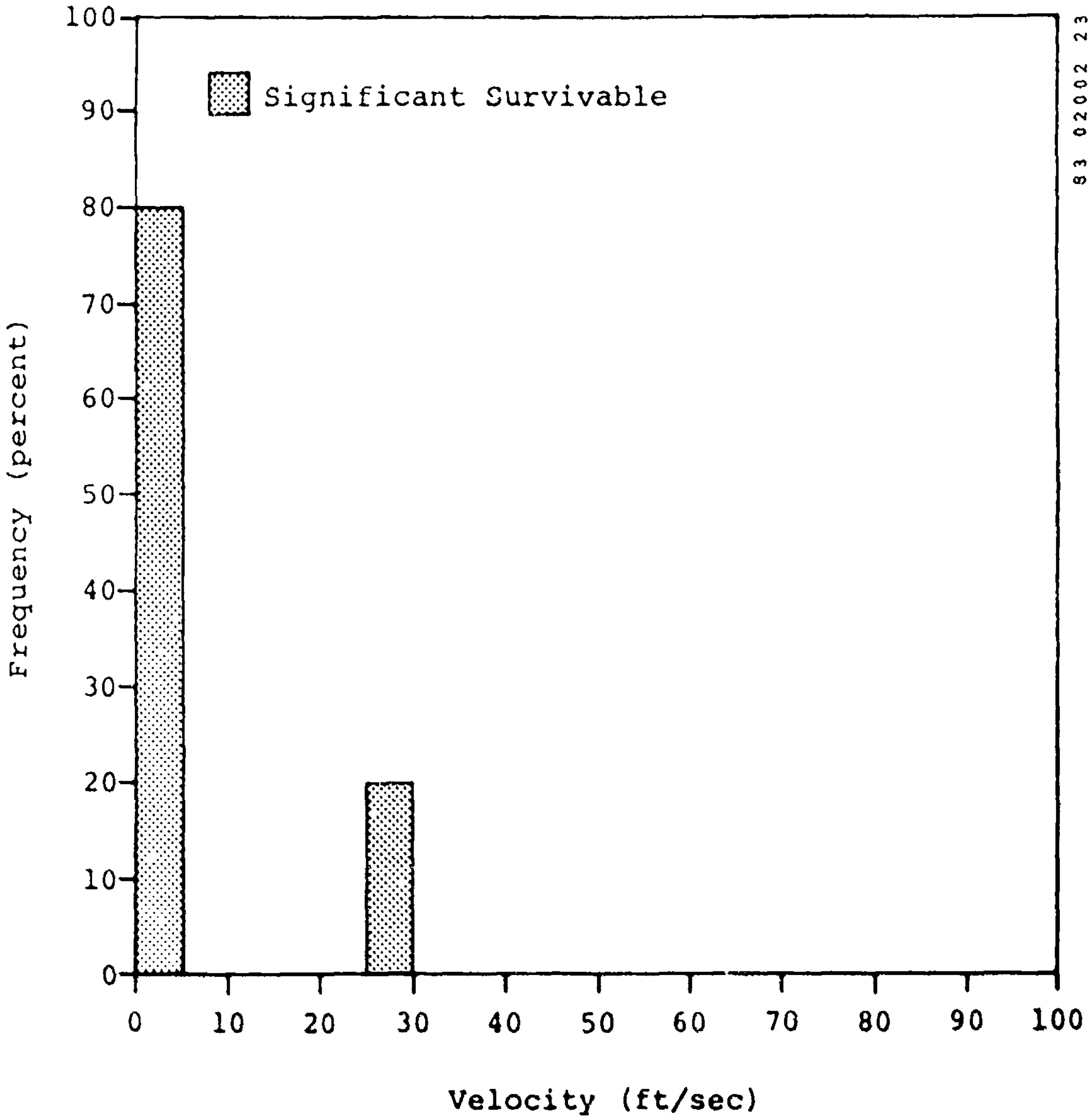


Figure F-8. Frequency of occurrence of longitudinal impact velocity, Weight Class D (5 accidents).

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